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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 14

Underwater Sound Equipment I

LISTENING SYSTEMS

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

- Division A — Armor and Ordnance
- Division B — Bombs, Fuels, Gases, & Chemical Problems
- Division C — Communication and Transportation
- Division D — Detection, Controls, and Instruments
- Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

- Division 1 — Ballistic Research
- Division 2 — Effects of Impact and Explosion
- Division 3 — Rocket Ordnance
- Division 4 — Ordnance Accessories
- Division 5 — New Missiles
- Division 6 — Sub-Surface Warfare
- Division 7 — Fire Control
- Division 8 — Explosives
- Division 9 — Chemistry
- Division 10 — Absorbents and Aerosols
- Division 11 — Chemical Engineering
- Division 12 — Transportation
- Division 13 — Electrical Communication
- Division 14 — Radar
- Division 15 — Radio Coordination
- Division 16 — Optics and Camouflage
- Division 17 — Physics
- Division 18 — War Metallurgy
- Division 19 — Miscellaneous
- Applied Mathematics Panel
- Applied Psychology Panel
- Committee on Propagation
- Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

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FOREWORD

In submarine warfare the term *listening* is used in a generalized sense to describe a variety of ways in which a ship, submarine, or torpedo may be made to betray its presence and location to a *listener* by the noise it makes. Such noises are picked up by a hydrophone or an array of hydrophones and, after suitable combination and amplification, are made to operate a loudspeaker, recorder, or other indicating device.

To be recognized by the ear, sound must be above a certain minimum intensity or energy level. Also, only those components of a sound are recognizable which lie in the *frequency spectrum* above a certain lower frequency and below a certain upper frequency. Further, to be recognized by the ear, a particular sound must not be masked by other sounds. This does not mean that sounds which, because of their low intensity are inaudible to the unaided ear, cannot by instrumental aids be made audible by amplification, nor that sounds outside of the audible frequency range cannot by instrumental methods be transformed to the audible range and thus made recognizable. Both industry and the military are vitally concerned with the art that has developed from these principles.

In addition to the pure-listening art, it is frequently desired to utilize the energy arriving from a sound source for purposes other than audible recognition. For example, sound energy can be used to supplement auditory recognition by visual or mechanical instrumentation, or even to explode a mine, or guide a torpedo to the sound source. Many of the physical factors pertinent to listening likewise apply to these other applications.

While listening techniques have many military applications, the program of Division 6 was generally limited to their application in antisubmarine and prosubmarine warfare. Even so restricted, these techniques are critically important. The NDRC and Navy agencies have made substantial progress in the development of listening methods, and large additions have been made to the knowledge of physical and physiological factors involved. However there is still room for much further research and development. Because sound is the only form of energy which water transmits without enormous energy losses as the distance from the source is increased, it appears that listening techniques will continue to be important in subsurface warfare.

The present volume, prepared by J. S. Coleman, J. W. Horton, and D. A. Proudfoot, does not cover all matters pertinent to the listening art. It is primarily a description of a number of listening devices developed by Division 6 with emphasis on instrumentation problems. Elsewhere in this series of technical reports are found the results of basic studies by the Division on the noise produced by surface ships, submarines, and torpedoes; on the propagation, attenuation, and scattering of sound in the sea; on background noise; on the effect of bottom and surface; and on countermeasures to enemy listening devices.

The development of listening devices was for the most part assigned by the Division to Columbia University's New London Laboratory and to the Bell Telephone Laboratories. The Underwater Sound Reference Laboratories also contributed to the work of these laboratories by making available facilities for standardizing measurements. Two factors are of supreme importance in the development of listening methods and devices: the behavior of sound in the ocean, and the performance of the human ear. As research continued at Woods Hole and San Diego, data on underwater sound were gradually accumulated and forwarded to the development engineers. The Bell Telephone Laboratories contributed to the project the results of many years of physiological research on hearing.

This general activity proceeded under several Navy projects, always receiving the most helpful support and liaison from the interested Bureaus. The Navy also furnished facilities for tests to supplement the facilities of the laboratories. In addition to maintaining close liaison with the Bureaus, in the later stages of development and operational use of devices, many contracts were made with COMINCH and the operating forces. In every case these contacts were most satisfactory.

No attempt has been made to ascribe credit for technical performance either to those who directed the work in the various organizations or to the individuals on their staffs. However it is but due his memory to mention particularly Dr. Albert L. Thuras who, for over four years, was a member of the New London Laboratory. He brought to his task rare enthusiasm and experimental skill. His contribution to the various projects was outstanding.

John T. Tate
Chief, Division 6

PREFACE

THIS REPORT is intended to summarize the work of the Division 6 laboratories on underwater listening devices and techniques applicable to the detection, navigation, and operation of submarine craft. It was prepared by the Summary Reports Group of the Columbia University Division of War Research on the basis of numerous technical progress and completion reports submitted by the participating contractors, together with certain supplementary material collected and organized into its present form by members and contributors to the group.

The programs and developments recounted were, for the most part, undertaken by the Columbia University Underwater Sound Laboratory at New London, Connecticut, and the Bell Telephone Laboratories in New York. Both groups have contributed significantly to our total of knowledge in this field. It is regretted that the very large number of their staff members, whose accomplishments are only partially recorded here, makes it impossible to give individual credit.

The volume is not intended to serve in any sense as a textbook but as a reference useful to newcomers to this rather specialized art, who may wish to acquire background, as well as to those who may be interested in particular details and the reasoning behind the electronic techniques and circuitry employed.

As editor of the volume, I should like to acknowledge the assistance of Donald E. Proudfoot and William J. Meringer of the SRG staff, of J. Warren Horton of the Massachusetts Institute of Technology who prepared the chapter on Evolution of Listening Gear, and to the Bell Telephone Laboratories and the naval staff of the United States Navy Underwater Sound Laboratory at New London who were extremely helpful in providing the many charts, diagrams, and photographs which illustrate the text.

JOHN S. COLEMAN
Editor

CONTENTS

Chapter 1

INTRODUCTION TO LISTENING

SOUND, BROADLY DEFINED, is the only form of energy which can be transmitted any considerable distance underwater. Important civilian and military developments stem from this physical fact. In some cases a source of sound energy is *intentionally* provided, as in underwater communication and echo-ranging systems, while in other cases the source of sound energy utilized is incidental to the operation of vessels or weapons in the water, such as surface ships, submarines, and torpedoes. Such sound energy may be employed to determine the presence and location of its source. In this process of determination, commonly called detection, the ability of the ear to discriminate and to identify characteristic sound patterns has stimulated development of a listening art and numerous pieces of gear termed *listening devices*.

Although the energy radiated from a sound source such as a moving surface ship or submarine has had important uses for the Navy and the Division other than to determine the presence and location of the source, this report is limited to developments in the field of listening gear and its supplementary devices. It does not include listening as a sequence of echo ranging, in which the reflecting surface of a structure in the water becomes, as it were, a sound source to be detected and located. Advances in such applications of the listening art, however, naturally parallel those in "pure" listening, and it should be noted that echo-ranging gear may be used for listening to sounds other than the echo, a supplementary use which is of great tactical importance. The two arts of echo ranging and listening in fact very much overlap, and in actual military operations one supplements the other.

In World War I, the problem of detecting and locating the submarine was attacked by modifying existing air listening devices to serve underwater both for submarine and surface craft. Since knowledge of the techniques of electronic amplification was scant and hydrophones inefficient, such equipment was only moderately effective. That it was effective at all was attributable only to the extremely noisy submarines then in service. Following the tactical employment of listening equipment, a countereffort was made to quiet the submarine, particularly during the period of evasion. The success of this effort so reduced the range of listening gear as to make detection almost impossible except at extremely short ranges. A partial answer was found in echo-ranging gear which, relying on the echo of its own signal, again permitted the attainment of useful target ranges. As no entirely successful countermeasure to reduce echo strength has yet been devised, this method has received the major development effort in the field of antisubmarine warfare.

The same knowledge and developments, however, that have advanced the design of echo-ranging gear have also advanced the design of listening gear, since listening is, essentially, the second half of echo ranging. Better hydrophones, efficient amplifiers, and an increased understanding of the phenomena involved have brought corresponding extensions of range and flexibility of application. Although, in general, the extreme quietness of operation possible with modern submarines has made it inadvisable to rely on listening gear for their positive detection, in certain tactical situations listening offers a number of advantages that may have increasing importance.

1.1 VIRTUES OF LISTENING METHODS

TACTICAL SECURITY

The operation of any detection system which depends upon echoes of its own signal can be detected in turn at far greater ranges than its own maximum range. The use of echo ranging or radar, therefore, not only may jeopardize own-ship's security but also inherently presents

the possibility of giving the enemy more information than can be received. Worse, because of the range difference, it may warn the enemy out of range and thus destroy the chance of securing any information at all. It is sometimes possible to select transmission frequencies or wavelengths which are believed not available to the enemy and thus obtain some measure of security. However, with the increasing use of panoramic receivers and the physical limitations of available spectrum, such a measure can only be regarded as temporary.

The advantage of security offered by listening is of particular importance to the submarine. This is true both when it is submerged and when it is surfaced, for, since no energy is radiated, it is possible for the submarine to secure information concerning the position and movements of the enemy without increasing its own detectability. In this respect, listening is comparable to optical scanning methods when surfaced. With the submarine submerged, the security advantage of listening is greater, since the periscope is detectable by both radar and optical means. Also, the use of the periscope restricts the submarine to shallow submergence depths where it may be detected by its shadow or silhouette from the air.

It is interesting to note that maximum range and bearing accuracy have been so improved in listening gear for submarines that a successful torpedo attack has been conducted using no other target information than that obtained from the listening gear.

Maximum Range

Except for very quiet targets, listening methods permit detection at a greater maximum range than do echo ranging. The two methods provide equal ranges only when the signal-to-noise ratio of the returning echo is at least equal to that for the target noise signal. As the echo-ranging signal must travel the range distance twice and suffers also from imperfect reflection by the target, it is subject to much greater losses than is the listening signal. Calculation of these losses shows that the original acoustic output necessary to secure a detectable echo from a typical target gets uncomfortably large for ranges exceeding a few thousand yards. Thus, while under favorable conditions echo ranges of 2,000 to 4,000 yards are considered good, submarines using listening gear often detect surface targets at 20,000 yards and more. Unfortunately for surface craft applications of listening, modern submarines, by reducing speed and stopping auxiliaries, can be operated so quietly as to be completely inaudible at ranges greater than a few hundred feet. An equivalent tactic on the part of surface ships, however, would obviously result in the loss of their function if not in their destruction.

In the course of World War II, American submarines were able to use radar for long-range search and were not forced to rely on listening gear. As long as no loss in ship security is involved, this method, giving both range and bearing, is to be recommended over present-day listening systems which give less accurate bearings and only approximate ranges. However, it is not unlikely that it will soon be necessary to maintain radar silence as well as radio silence. This probability, together with the advent of greatly increased speeds, and therefore noise, for both submarine and surface craft, indicates that listening will play a more important role in establishing long-range contact.

Continuity of Information

Listening methods provide continuous rather than intermittent information. While this feature is less significant where high velocities of propagation permit extremely short cycling periods, as in the case of radar, it becomes a very real advantage in the case of sonar. Sound in water travels at less than 1 mile per second. With conventional echo-ranging gear, this means that for maximum search ranges of 4,000 yards information is received for only a few hundredths of a second every 5 seconds. At 1,000 yards this interval is reduced to about 1.2 seconds. Further, because of the variability of amplitude, phase, and path taken by the echo and because of the difficulty in keeping the projector trained accurately on the target, it is generally necessary to take several readings.

The continuous flow of information received by listening gear, contrasted with echo ranging, not only permits adjusting gain and selectivity controls for optimum signal discrimination but also, because of the operator's ability to average with time, permits securing more accurate bearings. With the development of more precise bearing indicators, this ability of listening gear becomes of increasing interest. Precise bearings permit obtaining accurate bearing rates which are useful in computing target course and speed. Thus, with *triangulation-listening-ranging* [TLR] gear, it may soon be possible to supply all information necessary to a computer for a torpedo attack.

Wide-Band Coverage

Still another advantage of importance is the ability of listening gear to accept a wide-frequency spectrum. This enables simultaneous reception of the lower sonic frequencies which are useful in determining the nature of the target as well as the higher frequencies which permit accurate determination of bearing. Also it enables the operator to select quickly and concentrate upon any distinctive frequency band in which the target may be particularly noisy. This is possible because target sounds are rarely monochromatic except when the target is echo ranging, in which case the advantages of wide-band reception are obvious.

Simplicity of Equipment

A further advantage arises in the reduced amount of equipment required. Not only can listening gear be made with less than half the bulk of echo-ranging gear but, perhaps even more important, it requires only a small fraction of the power to operate. This, of course, is of particular interest in the case of small craft and submarines where space and efficiency are primary considerations.

1.2 FACTORS AFFECTING PERFORMANCE

Detection of a target by listening is a complex matter which depends not only on the original characteristics of the noise signal but upon the transformations and losses suffered during transmission through both the sea and the acoustic system employed. It is also highly dependent upon the ability of the operator to recognize and identify characteristic sounds against a masking beckground which is in large measure uncontrollable.

The sea is by no means a homogenous, isotropic medium. Variations in temperature, salinity, ocean bottom, and surface all affect the propagation of sound. Transmission losses result both from the spreading of the sound intensity and from attenuation due to scattering and absorption. Reflections from the surface and bottom introduce phase errors, while refractions, caused principally by temperature gradients in the water, may bend the sound path so severely that reception is impossible except at extremely short ranges. Ambient noise present in the water, distinct from the self-noise of the ship and listening equipment, may be caused by surface conditions, marine life, or other ships. In coastal waters, man-made noises may reach high levels.[a]

The problem confronting the designer of equipment for underwater listening has two main aspects: first, the extension of the effective range of initial detection and identification of the target; second, the improvement of the accuracy of bearing determinations.

Extension of Range

Maximum range for a listening system is always determined by the signal-to-noise ratio. Consequently, extensions of range can only be accomplished by increasing this ratio. Assuming a fixed signal at the hydrophone, this can be done only by lowering the noise. Amplifiers and hydrophones now available have made it possible to eliminate electric noise as a factor. Self-noise, generated by the vessel's machinery and motion through the water, can be greatly reduced by the use of antivibration mountings, acoustic insulation methods, and proper streamlining. Although such measures have not yet been fully exploited, they have succeeded in reducing the importance of self-noise as a

[a] These basic factors relating to the behavior of sound in the sea have been extensively investigated and are discussed in detail in Division 6, Volumes 7 through 9. They are also reviewed briefly in Chapter 3.

factor in submarine installations for all except the higher submerged speeds. Self-noise continues to be the limiting factor for sonic frequencies in surface craft except for very low speeds.

Under conditions of low self-noise, signal-to-noise ratios are determined by the background noise present in the water. The effects of such random noise can usually be reduced by making the hydrophone more directional, so that it responds only to sound coming from a narrow angle. The two factors that impose a limit on improvement from this direction are the dimensions of the hydrophone and the uselessness of a needle-sharp beam for search operation.

A study of the problems of extension of range and improvement in bearing accuracy leads to a consideration of the directivity of the hydrophone. There are many arguments for making the hydrophone very directive. Not only is the signal-to-noise ratio improved by the exclusion of random noise from all directions but also it is obviously easier to determine direction accurately if a narrow-beam pattern is provided. On the other hand the provision of a too narrow beam slows up the rate at which a given sector of ocean can be scanned. A compromise must therefore be drawn between extension of range and scanning rate.

Improvement of Bearing Accuracy

Improvement of bearing accuracy is essentially an engineering problem and is largely dependent upon the beam pattern of the hydrophone: beam width, directivity index, side lobes, and rear response. All these are, in turn dependent upon the structure of the hydrophone and the frequency of incident signals. Steering may be accomplished by mechanical training or electrically by introducing appropriate phase lags between members of an array of hydrophones. Bearing accuracy has been further increased by the technique of split pattern hydrophones in which the direction of maximum signal is determined by comparing the response of two separate patterns and discriminating electrically on the basis of phase or amplitude differences between the two. Such systems can be made very sensitive and have the additional feature of indicating the direction of error in bearing.[b]

In Chapter 6 of this volume, attention is given to the *phase-actuated locator* [PAL] and the *right-left indicator* [RLI].

1.3 ANTISUBMARINE APPLICATIONS

Patrol Craft Systems

The first application of listening gear by Division 6 to a tactical problem was dictated by urgency. The years 1942 and 1943 were marked by a sharp upsurge in U-boat activity against our Navy and Merchant Marine. With few sonar-equipped antisubmarine vessels available for patrol and convoy work, hasty efforts were made to develop a simple listening system that would enable small converted civilian craft to assist in coastal patrol. It was felt that although such craft were not equipped to attack and destroy submarines, they could detect and localize the targets until help could be summoned. Later, the Navy found it possible to provide ever increasing numbers of better-equipped military craft. Consequently, the oversimplified listening gear produced for this purpose was not put into actual service.

The information gained in this program, however, was extremely valuable and became applicable to all sonar designs. Significant contributions were made to the analysis of typical target noises and the evaluation of the effectiveness of various design parameters of the detecting gear. Chapters 4 and 5 of this volume review some of this basic work.

The Radio Sono Buoys

At present it is generally true that echo ranging is more effective in the detection of submarines than is direct listening. As pointed out previously, this results from the extreme quietness of the modern submarine when submerged. It also is a result of the very high self-noise in the useful sonic region of destroyers at patrol or attack speeds. The principal contribution of listening gear in the field of anti-

[b] The reader is referred to Division 6, Volume 15, for a general discussion of *bearing deviation indicator* [BDI] systems.

submarine warfare, the radio sono buoy, avoids this difficulty.

Essentially, the radio sono buoy is a small, rugged, sonic listening system which is capable of transmitting by radio the underwater sounds it picks up. As the receiver can be remotely located either in an aircraft or a surface ship and can be instantly tuned to any one of a number of buoys, it makes possible the detection and tracking of submarines within the range of its hydrophone. By removing the noise of a searching ship, the ranges obtainable with these buoys are often considerable, since the submarine, having no immediate cause for suspicion, is not rigged for silent running. Later versions of these buoys added the feature of directivity (*directional radio sono buoy* [DRSB]) and thus not only extended their range but also provided with a single buoy a geographical bearing of the submarine's position.

These buoys found their principal use in permitting aircraft to establish contact with submerged U-boats. They were extremely successful in this application. A later application of great value was in their use in the last days of the war by surface craft in the English channel against U-boats operating with Schnorkel.

1.4 THE PROSUBMARINE PROGRAM

Because of the nature of the several factors involved, an effective application of listening gear is in the field of prosubmarine activity. A submarine is a weapon of stealth and must, to maintain its usefulness, operate unobserved and undetected. On the other hand, surface craft, the submarine's natural enemies and prey, are as a class noisy and therefore ideal targets for a sonic listening system. Further, during the submerged evasion period when the submarine is most helpless, the sonic contact it is able to establish is its one means of obtaining information concerning the number, disposition, and intent of its attackers.

A typical submarine sonar installation includes equipment for echo sounding to determine depth of bottom, for echo ranging to determine precise target and minefield location, for supersonic listening, usually utilizing part of the echo-ranging gear, and for sonic listening, usually from hull or topside-mounted gear for general-purpose use.

Use of Echo Ranging

The submarine uses its echo-ranging gear for navigation, locating channels, charting minefields, and operating under conditions when other aids fail. Under wartime conditions in enemy waters or in the neighborhood of enemy craft when security is paramount, its use is avoided. An exception is made only when, for purposes of obtaining a final range on a target before launching a torpedo, a single ping is emitted. The reason for this is demonstrated by Figure 1, which shows that a typical condition, giving a maximum echo-range of 1,000 yards, permits the detection of the pulse transmission at a range of over 10,000 yards by an enemy alert in that direction.

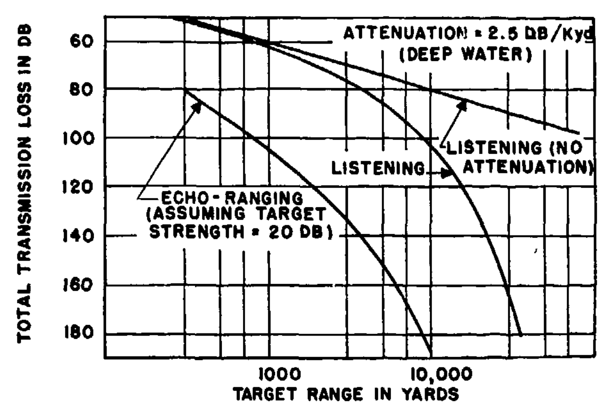


FIGURE 1. Total transmission loss for echo ranging and listening signals with range.

Use of Listening

Listening gear, on the other hand, is in almost constant use during submerged patrol and attack operations. In the Pacific war against the Japanese, our submarines found it desirable to make full use of radar and the periscope for long- and medium-range detection. This was possible, however, only because of the inadequacy and poor design of Japanese radar. It cannot be assumed that this condition will obtain with any future enemy. Below periscope and radar depth and at short ranges, reliance must be placed on listening.

To the uninitiated, the amount of information that can be secured by a trained operator with efficient listening gear is remarkable. Ships can not only be detected but also can be identified as merchantmen, destroyers, or battleships at ranges of thousands of yards. An extreme range of 42,000 yards (21 nautical miles) was verified on a battleship. Further, it has been demonstrated that bearing accuracies of better than 0.25 degree can be consistently realized by using split hydrophone techniques. Such performance has been made possible in this country only during the course of World War II and is ascribable to several developments. The first of these is the use of sonic frequencies. Supersonic listening gear, already installed in many submarines before the war, was preferred because of the lower noise background levels in the higher frequencies and because of the large hydrophone dimensions required for good directivity at the lower sonic frequencies. Little was known of the character of target noise or of the attenuation characteristics of water. As information was acquired on these subjects and the usefulness of the sonic band for maximum range and target identification was realized, a determined effort was made to develop an adequate hydrophone.

The line hydrophone, the second major development, made possible the reception of sonic frequencies with good directivity, which is the measure of the ability of a hydrophone to discriminate against noise. Built in the form of a long, small-diameter tube, the line hydrophone, when mounted, is highly directional in a horizontal plane and nondirectional in a vertical plane. This latter pattern is considered desirable, since it permits following a target having a high vertical angle.

Finally, improved amplifiers utilizing the favorable signal-to-noise and wide-band characteristics of the line hydrophone provided ideal reproduction of sounds over the entire sonic region and, by means of a heterodyne converter, over the supersonic region. With split hydrophones, specialized circuits were able to furnish highly accurate bearing indications by comparing electrically the time of arrival of the signal at each of the two hydrophone sections.

A most useful application of listening is that of torpedo detection. This was accomplished by the simple expedient of plotting the amplified output of a continuously rotated hydrophone on a bearing recorder. Not only can the torpedo be detected almost at the instant of launching but also it is possible to tell whether the torpedo's course leads, lags, or intercepts the course of the listening ship.

Aircraft Detection

A task yet to be solved is the detection of enemy aircraft in the vicinity above the submerged submarines. Had such equipment been available to the Germans in the last years of the war, it might have saved the majority of their submarines sunk by radar-equipped aircraft. Because, with present armament, the surfacing submarine is helpless for an appreciable period, the advantage lies with high-speed attacking aircraft. Preliminary studies have shown the infeasibility of detecting the noise of aircraft under water at any useful range. This is due, primarily, to the very high losses airborne sound suffers when entering water. It is suggested, however, that the principle of the sono buoy, inverted to serve as an acoustic transformer from air to water, may provide a possible solution to this problem.

Succeeding chapters of this volume review the evolution of listening systems, discuss typical experimental techniques and data, and, in the final chapters, present a detailed report of the principal equipment developments accomplished by Division 6 laboratories.

Chapter 2

EVOLUTION OF LISTENING GEAR

2.1 EARLY SONIC BEACON

UNDERWATER BELLS

UNDERWATER SOUND waves were employed as navigation aids for many years prior to World War I. During this period a considerable number of underwater bells were installed as part of coastal beacon systems. The sound waves emitted by these bells were picked up by electroacoustic devices which used a metallic diaphragm equipped with an inertia-type carbon button microphone. The diaphragm was, in general, responsive only to a limited range of frequencies, including the characteristic frequency of the bell to be detected. Hydrophones of this type were generally mounted in pairs in tanks located in the fore peak of the vessel, one on either side of the bow. Some indication of the direction of the bell could, therefore, be obtained by comparing the relative response of the two units.

THE FESSENDEN OSCILLATOR

Immediately prior to World War I, production designs had been completed on the Fessenden oscillator which was intended to provide a more effective source of underwater sound than the bells which had previously been used. The Fessenden oscillator consisted of a structure weighing several hundred pounds and having a heavy diaphragm resonant at approximately 500 c. This diaphragm was driven electromagnetically, the coupling being effected through eddy currents set up in the diaphragm itself. The electric input to the Fessenden oscillator was obtained from a motor-driven alternator. Experience with the oscillator demonstrated that it could be used for reception as well as for transmission of underwater sound waves having frequencies near that to which it was tuned. For such reception it was necessary merely to provide a proper polarizing current and to connect a conventional telephone receiver, or headset, to the oscillator terminals. For normal navigation use, it was intended that vessels should be equipped with carbon button hydrophones tuned to the oscillator frequency. The oscillators were to be mounted at designated points along the coast where they would serve as sonic beacons.

2.2 WORLD WAR I SYSTEMS

Systems using either the submarine bell or the Fessenden oscillator may properly be classed as communication systems, inasmuch as they include transmitting stations capable of sending signals based upon a prearranged code.

It was discovered that either the carbon button hydrophone or the Fessenden oscillator, used as a receiving device, was capable of picking up sounds which might be present in the water due to natural causes. Sound due to the propellers or to the machinery of ships, for example, could be detected, provided these sounds contained components having frequencies within the narrow band to which the response of the hydrophones was restricted. The first step toward the detection of moving vessels by means of underwater sound waves, therefore, had been taken prior to 1917.

Immediately upon our entry into World War I, attention was directed to the further developments of underwater acoustic devices as possible means of defense against enemy submarines. All U. S. submarines were equipped with Fessenden oscillators to enable them to signal one another while submerged. It was realized, however, that the limited range of frequencies to which the oscillator was responsive seriously limited its usefulness in listening for surface vessels. Superior detection devices with a wider range of frequencies were, therefore, diligently sought.

It must be remembered that during this period the vacuum-tube amplifier had not yet come into general use and that the efficiency of the pickup device itself determined its effectiveness to a far greater degree than is today the

case. As a result, much of the early effort was directed toward obtaining hydrophones the electric outputs of which were of sufficient magnitude to operate telephone receivers directly. The carbon button microphone continued to be used for a long time even though its inherent electric noise, as shown by subsequent measurements, is significantly above the level of its response to normal background noises.

MAGNETOPHONE

Toward the close of World War I, the development of electronic amplification had reached a point where hydrophones having both lower electric response to acoustic waves and lower internal circuit noise could be used advantageously. One such hydrophone, known as a magnetophone, employed a conventional telephone receiver as the electroacoustic transducer. This receiver was coupled acoustically to the water by means of a closed rubber tube. The magnetophone was capable of detecting both surface vessels and submarines at considerable distances. Its performance was not, however, enough better than that of the carbon hydrophone to justify the difficulties then attending the use of vacuum tubes.

ACOUSTIC SYSTEMS

Concurrently with the development of electroacoustic devices, considerable success was achieved in the use of purely acoustic listening methods. A metal tube, for example, closed at the lower end by a short length of rubber tubing, was found to bring underwater sounds directly to the ear of a listener almost as effectively as the electroacoustic devices. Such tubes were in use on our submarines until some time after our entry into World War II.

TOWED SYSTEMS

Even during early attempts at underwater listening, the electroacoustic devices exhibited one marked advantage over the simpler acoustic arrangements. The latter are seriously limited by the high level of background noise resulting from their mechanical contact with the listening vessel. Noises due to ship's machinery, to the activities of the crew, and to waves breaking against the hull all interfere with the reception of sound waves from a distant vessel. With the electroacoustic devices, however, it was possible to support the unit at a distance from the ship by means of suitable buoys and to carry the electric signals to the ship by means of a cable. This system had its obvious disadvantage in operation. Noises due to motion of the hydrophone through the water and to the listening vessel constituted an effective barrier to the reception of faint signals.

FREQUENCY COVERAGE

The best of the early listening devices, although markedly superior to the prewar resonant devices, nevertheless were responsive over a frequency range which was by no means extensive as compared with present-day electroacoustic systems. It is doubtful that these early hydrophones showed significant response to frequencies below 300 c or above 2,500 c. Over this region the response was far from uniform but passed through a maximum somewhere between 500 and 1,000 c.

Throughout the entire period of World War I, the development of listening systems was carried on without the benefit of reliable data on the frequency distribution of energy in sound waves set up by ships or in the noises interfering with their reception. Attempts were made to obtain such data but these barely reached the point of determining the response characteristics of the measuring equipment. They contributed virtually nothing toward the discovery of the optimum frequency or band of frequencies to be used for the detection of significant signals.

2.2.1 Bearing Determinations

Attention was next given to the possibility of determining bearing, or the direction of origin of underwater sounds. Two important contributions to the art were made. One was the so-called binaural method of listening, the other was the multispot array.

Binaural Systems

The first binaural system was purely acoustic. Two metal tubes were carried by a framework supported over the side of a listening vessel in such a way that the closed rubber terminating tubes which were separated by a horizontal distance of approximately 4 feet could be rotated in a horizontal plane. One tube led to each ear of the observer. As the tubes were rotated, it was observed that the apparent location of the signal source moved relative to the observer. When the line joining the two rubber terminating tubes was perpendicular to the direction of the source, the apparent location seemed to be directly in front of, or directly behind, the observer. The identification of position involved the interpretation of subjective sensations and required a considerable amount of practice. There are two bearings, differing by 180 degrees, for which the characteristic zero-position effect may be obtained. The true bearing of the source, however, may be identified by rotating the binaural pair away from its position perpendicular to the actual bearing and observing the direction in which the acoustic image appears to move.

Performance. The use of binaural tubes permitted the determination of bearing with reasonable reliability and thereby increased the utility of underwater sound in obtaining information regarding the position and movements of invisible enemy craft. Actually, the use of the binaural system did more than permit the determination of bearing: it increased the discrimination of the listening system for sounds from a localized source and helped to distinguish them from interfering random noise. A faint signal arriving along a definite bearing could be identified by its apparent movement when its relative intensity as compared with the intensities of interfering sounds was so low that it could not be recognized by a nondirectional system. In terms now familiar, the limiting signal-to-noise ratio for a binaural system is lower than for a simple nondirectional system. It must be emphasized, however, that this effective signal-to-noise advantage depends upon psychoacoustic sensations rather than upon measurable apparatus characteristics. It is, however, a very real advantage analogous to our ability to locate a squirrel in a tree more easily if he moves than if he remains motionless.

Electroacoustic Application. The capabilities of binaural listening proved to be so superior to those of simple nondirectional systems that the basic technique was applied to electroacoustic devices. Two hydrophones were mounted at a fixed separation and in fixed position and orientation in the water. Each hydrophone was connected by cable to a specially designed telephone receiver. The acoustic output of these, in turn, was led individually to the ears of the observer by means of ducts of adjustable lengths. By means of a calibrated control wheel, the lengths of these ducts were changed to give the same phase relations between the two signals as occurs in the simple acoustic system when the pickup units are set perpendicular to the bearing of the source. The acoustic phase shift device was known as a binaural compensator. The directional ambiguity which obviously appears in this case, as well as in the case previously described, was resolved by observing the indicated bearings obtained with two or more binaural pairs set in different orientations. Bearings which reappeared consistently were taken as the correct bearing.

Multispot Arrays

The second method for the determination of bearing, namely, the multispot array, depends upon the fact that the magnitude of the response of the system is a function of the relative bearing of the origin of the acoustic wave. The determination of bearing is effected by adjusting the position of the multispot array itself or by altering the phase relations of elements of the system so as to make the aggregate response to some particular sound a maximum. This work reached the point of establishing the great advantage of a directional listening device operating on the maximum intensity principle as a means for improving signal-to-noise ratio. It is important to note that, in spite of the improvements in hydrophones and in the use of electronic amplification achieved in recent years, the detection ranges possible with these early installations compared favor-

ably with the best detection ranges obtainable during World War II. One reason for this somewhat surprising fact is that the newer and more effective elements were never combined to form a multispot array having the acoustic dimensions of those used during World War I.

2.2.2 Military Applications

ANTISUBMARINE GEAR

The status of direct listening throughout the entire period of World War I may be summarized briefly. Submarines of that period were not particularly quiet. Most of those in operation had been planned, if not constructed, prior to the development of underwater listening equipment, hence there was no particular incentive to make them quiet. As soon as the potential capabilities of direct listening were appreciated, steps were taken to reduce the noise of our own submarines.

The first important application of direct listening was made from surface craft. It must be remembered that throughout World War I there was no effective method for the accurate determination of the range of a submerged submarine. The nearest approach to this essential information with the facilities then available was to use two or more vessels equipped with directional listening devices and to estimate the position and movements of the submarine on the basis of crossed bearing intersections. This arrangement was feasible because it required little movement on the part of the listening vessels, which was the only condition under which the gear of that time could be operated effectively in any case.

All these factors were reflected in the listening gear in use by surface vessels at the end of World War I. Three hydrophones were arranged to form three binaural pairs, the axes of which were spaced at 120-degree intervals. This system was carried to a distance from the listening vessel by means of a buoy and cable rigging. Proper orientation of the system depended upon such motion through the water as a ship lying to may possess due to wind pressure. Obviously, no great bearing accuracy could be expected under such conditions.

There was, throughout this period, almost no use made of listening gear by our own submarines. The absence of both radar and underwater echo ranging permitted the submariner to obtain practically all the information needed for an attack by means of the periscope.

HARBOR PROTECTION

A second important application of direct listening methods during World War I was in harbor protection. Here multiple binaural pairs similar to those described above were mounted on tripods planted on the ocean bottom at suitable locations near harbor entrance channels. These were connected to shore stations by electric cables. Provision was made for selecting any desired binaural pair by means of relays operated by pulses transmitted over the listening cables. Because of the accurately known positions of the tripods and because of the possibility of calibrating the orientation by means of a source having an accurately established position, these tripod systems were capable of great reliability in the determination of the position of any sound source within their range.

LISTENING UNDERWAY — MULTISPOT ARRAYS

The third important experimental development in direct listening which took place during World War I was in connection with multispot arrays. Models were built in which the individual units were carbon button hydrophones. These were connected independently to specially designed telephone receivers similar to those in the electroacoustic binaural systems. As in those systems the acoustic outputs were combined by ducts of adjustable lengths whereby the desired phase delays were introduced. The purpose in mind in developing these multispot arrays was to see whether sufficient improvement in signal-to-noise ratio might be obtained to permit operation from a vessel under way at moderate speed.

2.3 DIRECT LISTENING BETWEEN WORLD WARS I AND II

The period between World War I and World War II witnessed marked development of sonar equipment and methods. Supersonic echo-ranging equipment was one of the chief new

devices. The use of high frequencies made possible the construction of highly directive transducers of such size that they could be mounted and trained from a vessel moving through the water at considerable speed. The directional properties of these transducers gave adequate discrimination against locally generated noises so that echo signals could be received over sufficient range to have tactical utility for both search and attack operations.

The experience of World War I led to the designing of submarines capable of operating with very little noise. In fact, the range at which a submerged submarine might be detected with the best ship-mounted direct listening gear came, in time, to be considerably less than the range of detection possible by echo-ranging equipment.

Supersonic Listening

Finally, it was found that the highly directive echo-ranging projector could also be used for direct listening by heterodyning the received supersonic signals to produce a signal in the audible portion of the spectrum. Such direct listening in the supersonic region is, of course, subject to the same limitations with respect to signal-to-noise ratio as apply in the audible region although, in general, background noise is much reduced at higher frequencies. The directivity of the projector, however, gave a considerable advantage to operation at high frequencies. Comparable directivity at audio frequencies would have demanded transducers of prohibitive size, although it could have been obtained by multispot arrays.

Attenuation. Attenuation is one adverse aspect to direct listening at frequencies above the audible portion of the acoustic spectrum as the attenuation factor increases with frequency. This is of little significance at short distances but is of major importance whenever detection over long ranges is sought. Acoustic waves of high and of low frequency suffer about the same transmission loss in traveling a thousand yards from their source. At a range of 10,000 yards, however, a wave having a frequency of 30 kc is reduced in energy intensity some 650,000 times as much (58 db) as a 1-kc wave.

Further Development of Multispot Arrays

During the interval between the two World Wars, the multispot array was further developed in two ways. One was the use, in place of acoustic delay ducts, of electric delay networks and the introduction of the proper phase shifts directly into the electric outputs of the several hydrophone units. These outputs were then combined to form a single electric signal which could be made to show a maximum for a sound source on any desired bearing, depending upon the adjustment of the delay networks. The second improvement was the construction of harbor protection units for operation from fixed stations. These units were of considerable size, weighing approximately 16 tons and having a total span of approximately 50 feet. The array was divided into two 25-foot units. Each half was 4 wavelengths long at 800 c. It consequently had a high degree of directivity. The two 25-foot arrays were mounted along a single line which could be rotated in a horizontal plane. The hydrophones were so connected to telephone receivers at the shore station that each array functioned as one element of a binaural pair. The system as a whole, therefore, combined the objective signal-to-noise advantages of a maximum-intensity directional device with the subjective advantages of binaural operation. An installation arranged in this manner gives almost ideal direct listening.

2.4 DEVELOPMENTS DURING WORLD WAR II

With the renewed interest in underwater sound brought about by the imminence of a second world war, development of new devices in the field of direct listening was again actively resumed. At this time, however, the science of acoustics had reached a point where work could be carried forward on a firm quantitative basis rather than by trial and error. The availability of accurate standards for the measurement of the intensities and behavior of acoustic waves in water and for the determination of the performance characteristics of listening devices contributed to rapid advance.

Studies to Determine Optimum Frequency Characteristics

One of the first steps in the renewed program was an empirical determination of the general relations between the frequency characteristic of a given listening system and its ability to detect a faint signal against interfering noises. The first observations were made with completely nondirectional systems. The ranges were compared at which sounds due to various types of ships could be identified through representative background noises by an observer listening on a pair of high-quality telephone receivers. It was noted that each observer showed an initial tendency to prefer systems responsive over the lower portion of the frequency spectrum, that is, to frequencies in the range below about 3,000 c. This tendency appeared to result from preconceived ideas of naturalness and it was interpreted to indicate that the sounds heard agreed with those which the observer expected to hear on the basis of his previous experience with airborne sounds associated with the movement of objects in water.

It was soon realized, however, that fidelity, as understood in connection with the high-quality reproduction of sounds by radio or phonograph, meant little with respect to the detection of underwater signals, particularly at low levels. Once this was recognized, it became evident that audio components having frequencies above 3,000 c were of great value. In fact, systems responsive to frequencies as high as 10,000 c appeared more promising than systems incapable of responding to these frequencies. It appeared to be advantageous under many conditions to exclude components having frequencies at the lower end of audible range. The conclusions based on these tests, which were of a purely subjective nature, were in agreement with actual measurements of the frequency characteristics of underwater sounds which indicated that the energy associated with ship sounds fell off with frequency less rapidly than does the energy associated with water noises due to waves, surf, and other causes.

It must be kept in mind that the character of the sound and the ability of the ear to recognize this character played an important part in fixing the actual relative level of signal with respect to noise at which detection became possible. Where detection depends solely upon the ability of some instrument to indicate a discernible change in the magnitude of its total reading, the change being identified with the source to be detected, it is probable that there would be found to exist a narrow band of frequencies, or even a single frequency, for which this change showed a maximum fractional value. Such a single frequency, however, would certainly depend upon the particular conditions existing at the time of the trial and would vary greatly with changing circumstances. The ability of the ear to recognize some identifying characteristic in a given signal permits the detection of this signal while at a much lower relative level with respect to interference than would be possible with any instrument measuring only total energy. This situation finds a familiar analogue in our ability to hear spoken words against a background of general noise even though the energy associated with the noise may be many times that associated with the speech. In the case of ship sounds, the rhythm of the propeller beat often supplies the identifying characteristic. To permit the ear to recognize a given signal as a separate entity, it is necessary that the receiving system be responsive over some appreciable band of frequencies. This appears to be true even though the resultant signal-to-noise ratio, as measured in terms of absolute energy, is less than would be the case with a more restricted band. The ear itself is capable of applying selective discrimination to the several components making up the total signal delivered by the listening system.

Electroacoustic Transducer Status

The conclusions reached as a result of the experiments described above would have been of little practical value had it not been that the art of constructing electroacoustic transducers had reached a point where the electric response to the lowest acoustic levels encountered exceeded the electric circuit noise. These transducers used the piezoelectric properties of plates of crystalline material or the magnetostrictive properties of certain metals. The

mechanical constants of these materials provide better electroacoustic coupling to water than is the case for transducers designed for use with airborne sounds. Although there are many differences between magnetostriction transducers and piezoelectric transducers, these concern design details rather than overall performance. Quantitative knowledge regarding both types is now so complete that almost any given combination of operating requirements may be met with equal success by either.

With these hydrophones detection is limited solely by signal-to-noise ratio rather than by actual sensitivity. The maximum range at which a given sound source may first be discovered is, however, not determined uniquely by this ratio but depends also upon the arrangement and operation of the system and the manner in which the ultimate indication is presented. Several methods have been used to improve the detectability of a signal which must be observed against a high level of interference.

Possible Methods of Improving Detection

The signal-to-noise ratio at which detection ceases to be possible may be reduced by the proper choice of the position and breadth of the listening frequency band. The ability of the ear to recognize a signal having some identifying characteristic likewise permits a reduction of this limiting signal-to-noise ratio. The use of a directive transducer in place of a nondirectional unit is accompanied by an effective improvement in signal-to-noise ratio. This, of course, results directly from the fact that with a directional receiver the signal is required to compete only with interfering noises arriving along the same bearing instead of with noises arriving from all directions. Further, if a directional transducer is trained squarely on the bearing of an approaching sound source, the signal-to-noise ratio obviously increases slowly and gradually. Such a signal is not noticed by a listener at as low a level as is a signal which stops or, even better, which starts abruptly. This effect can be obtained under the complete control of the listener by training a directive transducer across the bearing of the sound.

Finally there is the use of so-called crossed lobes. This is basically a method for employing a directional receiving system to improve bearing accuracy and at the same time to obtain information as to the sign of any deviation between the significant axis of the system and the actual bearing of a sound source. It requires two directional transducers or their equivalent, so associated that the two axes of maximum response are separated by a small angle. The indicating system is then arranged to report in some suitable manner the relative response to a given signal as received over the two paths. In particular, the bearing of a source in which the two responses are identical may be thus identified with far greater accuracy than the bearing of maximum response of either alone. This enhanced bearing discrimination is accompanied by an increase in the capability of the system to detect a faint sound when the critical axis is swept across the bearing of the sound at a suitable rate. The crossed bearing technique is of little if any value when the transducer system is maintained constantly on the bearing of an approaching sound source.

2.5 APPLICATIONS IN WORLD WAR II

Changes in combat methods and the development of new weapons during World War II are reflected in the differences between the performance characteristics of direct listening gear now used and that of World War I.

Radio Sono Buoys

An important innovation is the use of radar-equipped aircraft for search and attack in antisubmarine warfare. Once the target submarine is below the surface, however, radar is unable to supply further information as to its position and movements and it is frequently too late to obtain visual information of sufficient accuracy to permit reliable placement of depth charges. The *expendable radio sono buoy* [ERSB] provided a means whereby the necessary information could be obtained through the use of underwater sound. In this device, signals from the buoy to the listening station are carried by radio transmission and thus, by removing the necessity of maintaining mechanical contact,

greatly extend the separation possible. Since direct mechanical control of the unit is not possible after launching, the earlier models were provided with a nondirectional hydrophone in order that coverage of all bearings might be assured. This, however, reduces the signal-to-noise ratio below that which would be possible with a directional unit.

It has been common experience that the noise level of a free-floating radio sono buoy is appreciably lower than when anchored in a fixed position where it may be subject to tidal currents. Although the operation of the radio sono buoy obviously suffers no direct interference by acoustic noises generated by the airplane, severe masking interference arises from high noise levels inside the airplane. This situation can be alleviated to some degree by sound reduction and insulating measures and by raising the observer listening level with respect to the noise background. With a suitably designed system, detection of a submerged submarine is possible over ranges sufficient to have tactical value. Estimates of the position, course, and speed of a submarine are possible by comparison of the relative signal levels as heard over several units properly disposed in the vicinity of the target.

Toward the close of the war, designs were worked out for a *directional radio sono buoy* [DRSB] containing a compass mechanism which, by altering the carrier frequency, permits continuous determination of the magnetic bearing of the transducer axis. In addition to the primary advantage of giving more complete and reliable information as to position, the directional buoy possesses greater detection ability than does the nondirectional form. Part of this improved detection ability comes from direct discrimination of the hydrophone and part from the fact that the location of the sound source is traversed by the directive beam so that the response, being of momentary duration, is more conspicuous than if it were received without interruption.

Line Hydrophones

One of the more important developments relating to direct listening to be completed during World War II was the so-called line hydrophone. This was made available both in magnetostriction and in piezoelectric types. Line hydrophones exhibit maximum response to sources located on any bearing lying in a plane perpendicular to their mechanical axis. Directivity patterns taken in any plane passing through this mechanical axis, however, show a marked decrease in sensitivity as the bearing of a sound source departs from the perpendicular. Although a hydrophone in which maximum response is limited to a plane only does not have so effective discrimination against background noise as one in which it is restricted to a single line, these directivity characteristics have certain practical advantages. The chief of these results from the fact that a line hydrophone, mounted with its axis in the horizontal plane, is not so liable to lose contact with a target with change of depth as is a hydrophone having discrimination on all bearings off its acoustic axis.

Applications. A number of important applications of the line hydrophone were made during World War II. Perhaps the most important was in providing sonic listening for our own submarines. Prior to the installation of line hydrophones as topside listening units, the only direct listening available to our submarines was by the supersonic echo-ranging equipment or by C tubes, simple acoustic pickup units arranged for binaural listening. These, it may be recalled, were developed during World War I and had been installed as replacements for the earlier Fessenden oscillator.

Line hydrophones were also installed on patrol craft by what were known as through-the-hull mountings. These supported the unit several feet below the keel and permitted it to be trained in a horizontal plane by means of a hand wheel inside the hull. In the case of a surface ship, however, the background noise level is considerably higher than in the case of a submarine and it is difficult, if not impossible, to use the line hydrophone effectively except when the vessel is lying to. With the submarine, on the other hand, almost no impairment of performance occurs at any normal submerged speeds.

Use was also made of the line hydrophone in connection with harbor defense installations. In some cases the hydrophones were mounted

on tripods and connected to shore stations by electric conducting cables. In other cases they were supported from anchored buoys containing r' lio transmitters. The buoys used for this purpose differed from the ERSB chiefly in the use of lower carrier frequencies, higher transmitting powers, and batteries suitable for continuous operation over long periods. Since the buoy was naturally much larger and heavier than the radio sono buoy, it was possible to employ a more effective antenna system. Many units, in fact, were equipped with a groundloop antenna.

Investigations of the Binaural Effect

Although practically no use was made of binaural listening during World War II, its possibilities were not completely ignored and some small amount of experimental investigation was carried out. It had been learned during the interval between the two wars that the binaural effect is related to phase differences between the lower-frequency components reaching the two ears and to the relative amplitudes of the higher-frequency components. World War I systems operated by virtue of the first of these effects, since their response was restricted to the lower end of the audible spectrum. Once it is established that higher-frequency components improve the effectiveness of direct listening systems, it follows at once that they may similarly improve binaural listening. Such systems must, however, be arranged suitably to introduce these amplitude differences. In everyday listening to airborne sounds, amplitude differences are caused by the shielding effect of the head. In one underwater system investigated, these were obtained by mounting two matched line hydrophones in a horizontal plane, with their centers approximately 4 feet apart, and with the angle between the two units adjustable through some 10 degrees. When the planes of maximum response of the two units made an angle of about 5 degrees, it was found that the binaural effect obtained was quite satisfactory. With this arrangement the separation between hydrophone centers introduces the desired phase shifts between the two signals for all frequencies at which this is the determining factor. At higher frequencies, where the binaural effect depends upon relative amplitudes, the off-setting of the directivity characteristics produces the desired effect. Such brief trials as were made of this system indicated, in a qualitative manner, that they were superior to systems depending solely upon the relative phases of signal components. This arrangement, in addition to improving the binaural effect, simultaneously achieves a considerable direct signal-to-noise advantage due to the directional discrimination of the two units.

Visual Indicators and Recorders

Torpedo Detectors. The development of visual indicating or recording instruments in connection with systems directly responsive to underwater sounds has resulted in important practical applications. One of these has to do with the detection of approaching torpedoes. The significant performance characteristic of an indicator for this purpose may be called its differential sensitivity.[a] It is particularly necessary to maintain high differential sensitivity over a broad spread of initial background levels in the case of torpedo detection. Reception is accomplished by rotating the standard echo-ranging projector at a uniform rate to provide coverage of all bearings. It has the advantage, over a nondirectional device, of an improved signal-to-noise ratio, characteristic of all systems having directional discrimination, and of the enhanced prominence of signal increases of abrupt momentary duration. Experience with such systems, however, discloses that the background levels encountered at various positions during 1 revolution of the projector may vary as much as 40 db over an angle not including the submarine's own propellers. It is obviously desirable that the indicating system maintain high differential sensitivity at any level encountered. This requirement appears to be met with reasonable adequacy by the cathode-ray tube operated as a logarithmic deflection indi-

[a] The differential sensitivity expresses quantitatively the ability of the instrument clearly to report a change in the amount of total energy received which, in the absence of some other identifying characteristic, may be the only evidence of the presence of an enemy vessel.

cator. The cathode-ray tube has the added advantage that it may, at the same time, be so arranged as to indicate the bearing of any source causing the differential indication. Developments have been undertaken looking toward the utilization of the crossed-lobe principle for enhancing this effect further.

Automatic Target Followers [ATF]. Automatic control of the power training mechanism is another development pertaining to indicating devices. These automatic target-following devices[b] employ some version of the crossed lobe principle by which the response of the system may indicate the sign of any deviation from correct bearing and thereby properly apply the correct restoring control. In following automatically some given target, the level of general interfering background is, of course, more nearly constant than in the search procedure used for torpedo detection. The signal level at which the system is most sensitive to incremental changes may, therefore, be obtained by manual adjustment and readjustment. It is, however, still desirable to have the equipment reasonably sensitive to incremental changes over an appreciable spread of levels.

It has been demonstrated that devices for maintaining a projector automatically on the bearing of some target are capable of high bearing accuracy. This accuracy is, in fact, of such order that it is now possible to determine the range of a target vessel by crossed bearings from two projectors mounted at opposite ends of a submarine. The separation of the projectors is then used as a base line for triangulation. The anticipated development of this so-called *triangulation-listening-ranging* [TLR] promises to provide a most important instrumental aid to our submarines. During torpedo approach maneuvers, the commander requires as complete and accurate information as possible regarding the position of the target at any instant and also regarding its course and speed. Information as to position may be obtained with considerable accuracy by means of echo ranging. The repeated trials required to determine the rates of change of range and bearing and thus to establish course and speed are, however, undertaken only at great risk inasmuch as continued echo-ranging transmissions offer the enemy an opportunity to discover the position of the attacking submarine. TLR, on the other hand, maintains the desired continual flow of range and bearing data silently. The continuity of range and bearing data obtained by such a system not only provides quantitative information as to the rate of change of each of these quantities but actually further increases the inherent accuracy of the system by permitting statistical averages to be secured.

In the light of current trends in subsurface warfare techniques, there are indications that the advantages of TLR, as compared with present echo-ranging methods, will increase in importance as time goes on.

[b] See material pertaining to automatic target training [ATT], Volume 15, Division 6.

Chapter 3

PHYSICAL FACTORS AFFECTING THE TARGET SIGNAL

3.1 INTRODUCTION

The determination of expected performance of any listening system is obviously dependent upon a knowledge of the factors affecting the character and strength of the signal to be detected by the listening hydrophone. These include analysis of the noise emitted by the target, of the transmission characteristics of the conducting medium, and of the background noise through which the signal must be recognized.

These matters, being fundamental to the problem of detecting and locating a submerged target by means of sound, have been subject to continuous study by Division 6 laboratories and investigators.[a] Because, however, any discussion of underwater listening equipment must be accompanied by an understanding of the part these factors play in its design and performance, they are very briefly reviewed in the following sections.

3.2 NATURE OF TARGET NOISE

The intensity and character of sound emitted by a target determine, under good conditions, how far the target can be heard. In general, target signal spectra depend on the type of ship, the number of propellers, the ship speed, and other factors, and are composed of machinery noise and cavitation noise. The machinery noise is produced by the engine and various auxiliaries while the cavitation noise is produced by the motion of the propeller and arises from the formation and collapse of cavities in the water.

Surface Vessel Targets

Figure 1 shows average spectra of an idealized target with expected limits for high and low speeds. The spectrum of any individual target, however, shows peaks at various discrete frequencies. These peaks are usually a result of machinery noise and occur in the middle sonic region. Figure 2, the measured spectrum of an aircraft carrier, shows such a peak at approximately 1,100 C. Although the

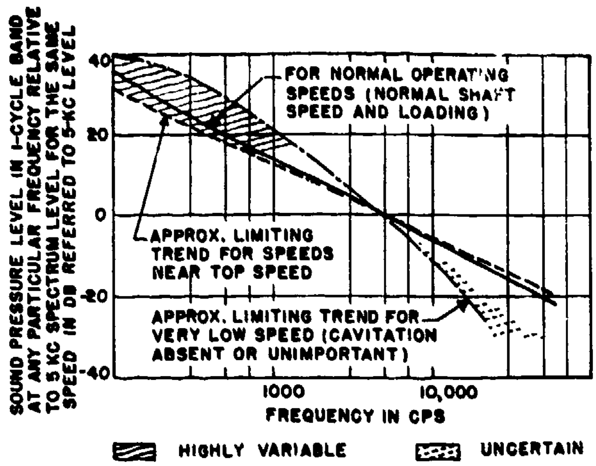


Figure 1. Average frequency spectra of an idealized target.

amplitude of this peak is unusually large, peaks of large amplitude at one or more frequencies are not uncommon.

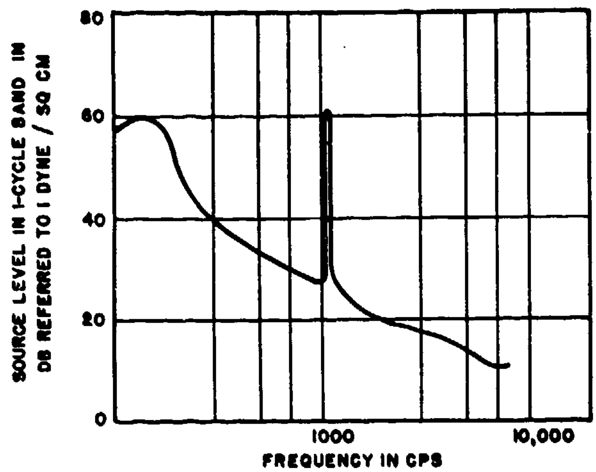


Figure 2. Measured spectrum of an aircraft carrier.

There are reasons for believing that machinery noise and cavitation noise have different spectral shapes. The spectrum of machinery

[a] See Division 6, Volumes 7 and 8.

noise usually falls off at high frequencies at the rate of 12 db per octave or more, although strong single-frequency components, depending on the details of the machinery, may exist. The slopes of observed cavitation noise spectra, in contrast, are always about −6 db per octave. Thus the spectrum levels of cavitation noise are likely to be greater than the spectrum levels of machinery noise at high frequencies. The importance of cavitation noise probably increases with increasing speed; at very high speeds cavitation noise may be dominant over the entire 0.1- to 10-kc band. Machinery noise is more likely to be greater at low frequencies, and its relative importance probably increases with decreasing speed; thus at very low speeds machinery noise may be dominant at all sonic frequencies.

At the speeds at which surface targets usually move, cavitation noise is ordinarily greater than machinery noise at most frequencies above a few hundred cycles. However, the spectrum level of machinery noise may exceed the spectrum level of cavitation noise at frequencies where there are large machinery peaks. Such machinery peaks can occur anywhere in the frequency band from 0.1 to 10 kc but are not likely to be dominant at frequencies above 2,000 c.

Identification of targets by listening appears possible only through recognition of machinery sounds or through recognition of characteristic propeller-beat modulations. Since machinery sounds cannot usually be heard at high frequencies, targets are probably more readily identifiable by sonic than by supersonic listening.

Experienced listeners, under favorable conditions, can distinguish between freighters, destroyers, battleships, and PT boats. Small boats can usually be distinguished from large boats. Some listeners can distinguish between empty and loaded freighters and between signals from targets at close range and at long range and can tell when a target changes course. Also, various other sounds can be recognized by sonic listening—torpedoes, depth charges, other submarines, airplanes, rain, fish noise, and noise from shoals and reefs.

Submarine Targets

In Figure 3 are plotted overall sound levels versus speed for large U. S. submarines at periscope depth. The dotted curve of the figure represents the expected radiated signal from the propellers, measured by a hydrophone 4 feet from the propeller tip. It is apparent that

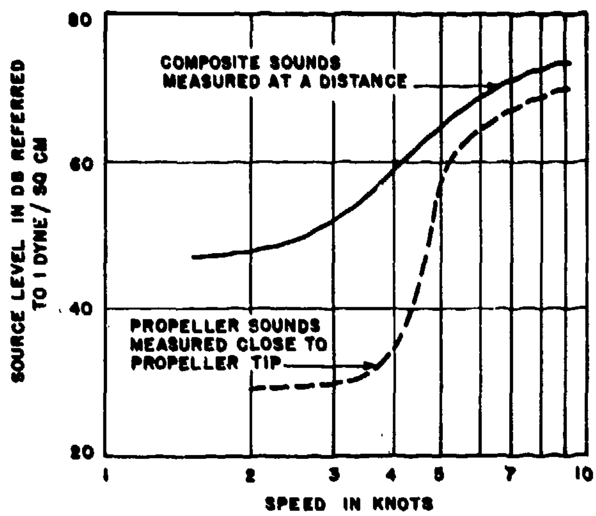


Figure 3. Overall sound levels for large U. S. submarines at periscope depth.

at speeds less than 4 knots the propellers contribute little to the composite energy radiated by the submarine. Though no reliable data exist, it is the opinion of most observers that at low speeds machinery sounds make up most of the radiated acoustic energy. This result is understandable, since cavitation usually does not occur at speeds below 4 knots.

One component of submarine target noise can be expected to show dependence on submarine depth. For a given speed, cavitation may be prominent when the submarine is near the surface and absent when the submarine is deeply submerged, since the speed at which cavitation sets in increases with increasing submarine depth. The other components of submarine target noise, such as noise from the motors and auxiliaries, should have little dependence on depth.

Torpedo Noise

Figure 4 is a composite of measurements on several different types of torpedoes. At sonic frequencies, measurements show little correlation with either torpedo speed or torpedo type. Torpedo noise frequently shows marked fluctuations in time, with high peaks of short duration. The spectra also show many peaks at distinct frequencies, sometimes at frequencies as high as 10,000 c. The high-frequency sound from a torpedo shows minima directly ahead of and behind the torpedo, with increasing directivity at the higher frequencies. However, at sonic frequencies this directivity is not very marked.

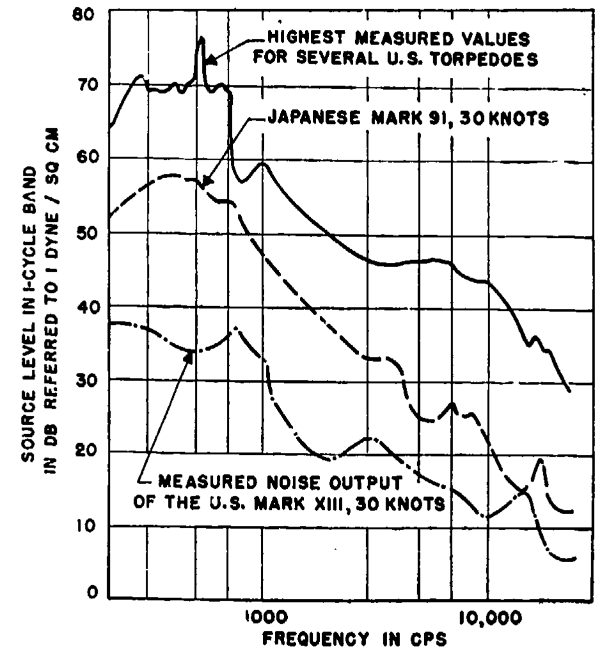


Figure 4. Noise measurements for several types of torpedoes.

Airplane Noise

Because of the much greater sound velocity in water than in air, a sound ray from the airplane striking the water at an angle of incidence greater than 13 degrees is totally reflected. Rays striking the water at angles less than 13 degrees are almost completely reflected, but some energy does enter the water. These entering rays are refracted through an angle which increases with increasing angle of incidence and become horizontal for the 13-degree critical angle where total reflection begins. This results in a very rapid decrease of intensity in the water with increasing horizontal range from the plane. At the longer ranges, the intensity in the water decreases at the rate of 12 db per doubled horizontal range, which means that, in general, the airplane can be heard in a submerged hydrophone only in that part of the ocean immediately beneath the airplane.

Figure 5 shows a typical airplane noise spectrum measured at the surface beneath a plane in level flight. Considerable data obtained by various investigators show that low frequencies predominate in airplane noise. Like torpedo noise, airplane noise often fluctuates markedly in time, with high peaks of short duration. Since the noise arises primarily from the propeller, harmonics of the propeller fundamental are prominent. The sound radiated by the airplane is highly directional, even at 100 c, with pronounced minima along the line of flight.

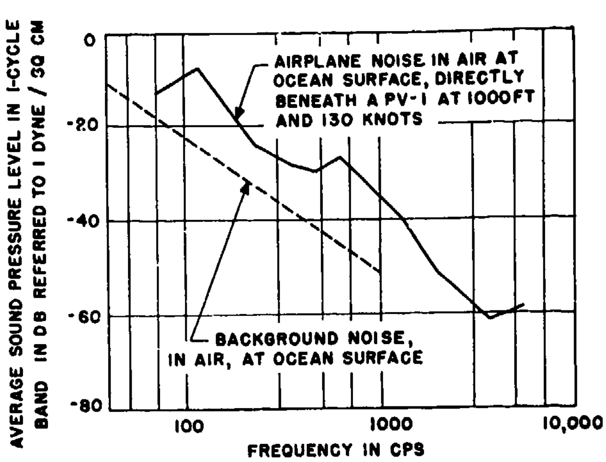


Figure 5. Airplane noise spectrum.

Explosion Waves

An explosion produces a shock wave consisting, at short ranges, of a very rapid, almost instantaneous increase in pressure followed by an exponential decrease with time. At ranges up to a few thousand yards, the peak pressure has a very simple dependence on the range (it

varies as the inverse 1.2 power of the range), and is almost independent of the weight of the depth charge. Thus, an estimate of the range of a depth charge explosion is possible from a measurement of the peak pressure of the pulse. An estimate of the bearing of the explosion, ahead or astern, to the port or starboard, and above or below, may be obtained by comparing the times of arrival of the pulse at appropriately situated pairs of hydrophones.

3.3 TRANSMISSION LOSSES

Spreading and Attenuation

Values of the transmission loss of sound in water at different frequencies are shown in Figure 6. Two effects are combined to give these curves. First, there is inverse square

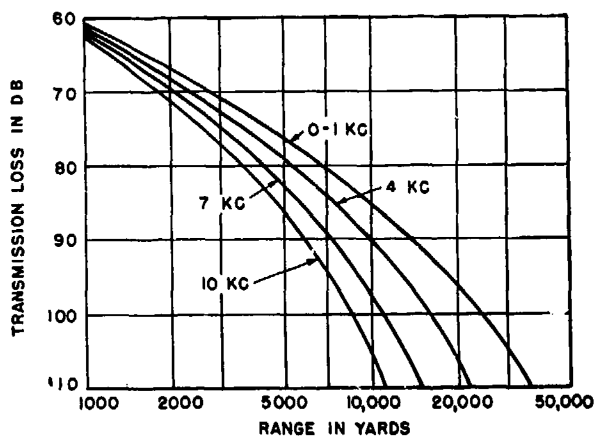


Figure 6. Transmission loss of sound in water.

spreading, which weakens the sound by 6 db each time the distance over which the sound travels is doubled. Secondly, there is scattering and absorption which weakens the sound by a fixed number of decibels each time a fixed distance such as 1,000 yards is added to the distance over which the sound travels. When transmission conditions are poor, as, for example, when temperature gradients are present near the surface, sound conditions are less well-understood; but, on the average, the attenuation coefficient for sonic frequencies under these conditions is about 2 db per kiloyard greater than in values given in Figure 6.

Reflection

Under certain conditions the sound intensity cannot be described as the result of inverse square spreading combined with absorption and scattering. For one thing, at ranges less than 2,000 yards, sound of frequencies less than 1,000 c may be markedly weakened by interference with surface-reflected sound, if the sound source and listening hydrophone are fairly close to the surface. This image effect (or Lloyd mirror effect) is unimportant for a submarine listening to distant surface vessels, but it may be important for a submarine wishing to evade sonic detection by nearby surface craft. Also, inverse square spreading may not be the rule at all ranges in deep water posses-

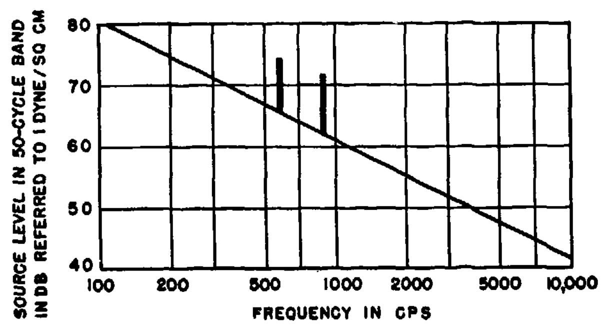


Figure 7. Sound output of a transport at 15 knots.

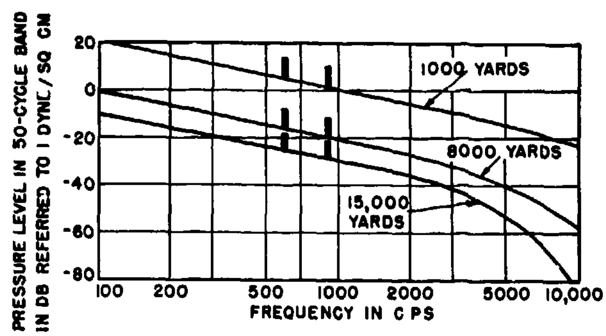


Figure 8. Weakening of sound by transmission losses.

sing strong negative temperature gradients or in shallow water with such temperature gradients over a soft mud bottom; for such oceanographic conditions, the downward bending of the sound rays may produce a shadow zone of very weak sound intensity at ranges beyond 500 yards or 1,000 yards. In deep water, this shadow zone should not extend beyond a range of

several times the depth; sound reflected from the bottom should begin to come in at such long ranges; and inverse square spreading and attenuation may be used to find the sound intensity as before.

Figure 7 gives the spectrum of the sound output from a 15-knot transport; Figure 8 shows the same sounds weakened by transmission out to ranges of 1,000 yards, 8,000 yards, and 15,000 yards. The transmission loss values are for the same good conditions portrayed in Figure 6. The assumed effect of absorption and scattering is evident in the progressive weakening of the high-frequency sounds.

3.4 BACKGROUND NOISE

When the target sound, modified by transmission, is received in the listening gear, it can be recognized if it can be distinguished from the other sounds heard in the loudspeaker or headphone. These unwanted sounds which tend to mask the sound being listened for are called background noise.

SELF-NOISE

The most important part of the background noise is the self-noise produced either by machinery inside the ship or by the motion of water around the ship and listening hydrophone. While the causes of self-noise in sonic gear have not been thoroughly investigated, the evidence indicates that most of the self-noise in JP-1 gear does not come from the submarine propellers. Measured self-noise levels in JP-1 gear, installed in new-construction submarines, give the average values shown by the upper dashed curve in Figure 9. For individual submarines, the individual values vary by 10 db or more above and below the average curve. The self-noise is observed to increase with speed; at 4 knots, 6 knots, and 8 knots, the levels are on the average about 3 db, 10 db, and 20 db respectively above the levels at 2 knots.

SYSTEM AND AMBIENT NOISE

If a submarine stops and turns off all its noisy auxiliaries, the only background noise present is electric or system noise which, at sonic frequencies, is unimportant for well-designed gear, and the ambient noise which is present in the sea independently of the submarine. Ambient noise in the deep ocean arises primarily from agitation of the sea surface, and increases with wind force or sea state. Noise levels from this source received by JP-1 gear in a number 2 sea state are shown by the lower dashed curve in Figure 9. Ambient noise,

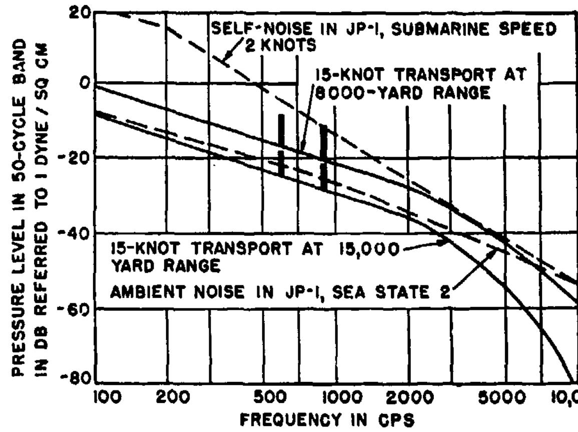


FIGURE 9. Background noise and target sounds in JP-1 gear.

like cavitation noise, decreases about 6 db per octave when measured with a nondirectional hydrophone. The increased slope above 1,000 c, evident in Figure 9, results from the directivity properties of the JP-1 gear.

3.5 TARGET VERSUS BACKGROUND NOISE

Also shown in Figure 9 are the target spectra at 8,000 yards and 15,000 yards taken from Figure 8. The target sound can be recognized at any frequency if, at that frequency, it is about as strong as the background noise. Thus screw sounds from the 15-knot transport can be heard at about 15,000 yards if self-noise is eliminated, whereas if the self-noise has the average value noted for JP-1 gear, these sounds can only just be heard at 8,000 yards. The recognition frequency is the frequency at which the target first becomes audible when the range is closed to maximum range. The recognition frequency is about 100 c for the lower pair of curves; however, listening at 1,000 c to 2,000 c

is only slightly less effective. When self-noise is important, the upper curves show that the recognition frequency for the cavitation sounds of this 15-knot transport is about 4,000 c.

Consideration of the machinery peaks changes somewhat the conclusions based on cavitation sounds alone. When self-noise is negligible, the machinery peaks of Figure 7 can be heard at about 20,000 yards. With all targets, machinery peaks of the height indicated can be heard at greater ranges than the cavitation sounds when self-noise can be neglected, though the range on the machinery peaks is rarely more than twice the range on screw sounds. When self-noise is high, however, machinery peaks of the height indicated in Figure 7 do not extend the range much, if at all. (See Figure 9 for an illustration of this point.) Sometimes peaks much higher than those of Figure 7 are present in target signals. High, easily audible peaks most often occur at 1,000 c or less; thus, to take full advantage of machinery peaks, background noise on submarines must be reduced at low frequencies.

Chapter 4

EXPERIMENTAL LISTENING SYSTEMS

4.1 INTRODUCTION

An investigation by the Bell Telephone Laboratories, Inc. [BTL] of underwater listening systems for use on small patrol craft was carried through the stages of preliminary survey, design, and construction of models, and installation on a small boat, the *Elcobel.* A description of the equipment and the tests made under controlled conditions is presented, since the basic principles and information gained are directly applicable to the design of detection systems for use on both submarines and surface craft.

This chapter describes four types of experimental systems which were designed and constructed for this service as a result of preliminary investigations and gives data on those characteristics of each system which determine its suitability as a detection device.

The following chapter discusses the results of field operating tests which were made in conjunction with Columbia University Division of War Research at the U. S. Navy Underwater Sound Laboratory, New London, Conn. [CUDWR-NLL]. These results are compared with the measured characteristics, and certain conclusions are drawn as to the value of the various systems and their components under operating conditions. These conclusions are summarized in a table of ratings which draws on all the information developed in this investigation, to mark each system according to its performance in each category.

4.2 THE ELECTRICALLY STEERED SONIC SYSTEM

Hydrophones and Circuits

A line array of six BTL No. 5 type hydrophones was mounted on 6-inch centers on each side of the hull of the *Elcobel* at a location representing the best compromise between maximum depth, distance from the propellers, and angle of incidence. The angle of incidence is the angle in a vertical plane between the face of the hydrophone and a sound ray from a source at the same depth as the hydrophone. A hydrophone mounted face down would have a zero angle of incidence.

Figure 1. 5B hydrophone assembly mounted in the hull of the *Elcobel.*

Depth is important because of the loss due to destructive interference between the direct sound waves and those reflected from the surface. The latter have more effect when the sound must travel close to the surface to reach the hydrophone. Distance from the propellers involves a loss of 6 db per double distance due to the divergence of the sound energy, plus whatever shielding can be obtained by interposing substantial portions of the hull between

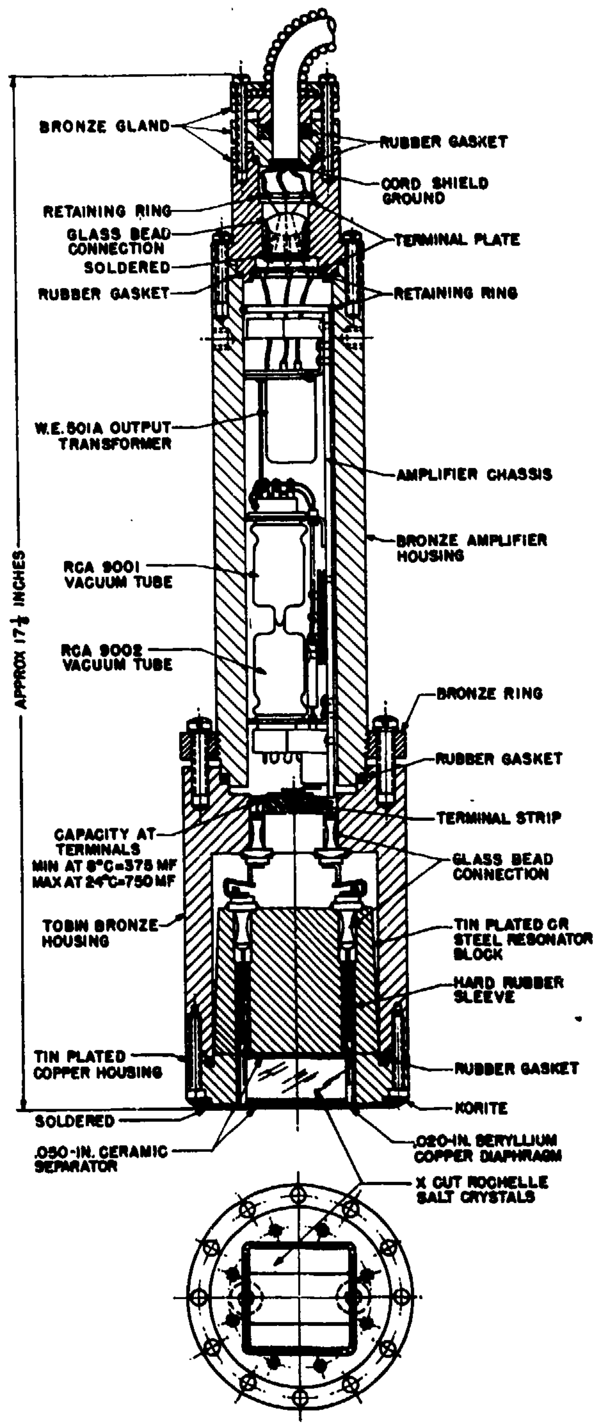


FIGURE 2. Electrically steered sonic system; cross section of 5A hydrophone.

the propellers and the hydrophones. The angle of incidence is again a question of the sound wave traveling along a reflecting surface, in this case the hull.

The location selected is shown in Figure 1. This view shows the hydrophones extending from the hull and arranged for mounting a protective cover. The arrays were 28 inches below the water line, 47 feet from the propellers at an angle of 40 degrees with the vertical.

Hydrophones. The No. 5-type hydrophone,[1] developed for use on the *Elcobel*, was designed to meet certain requirements derived from the preliminary survey. It was found that the listening-range limitation of existing hydrophones of small size was their noise threshold. The No. 5 type was designed for a threshold in the order of −75 db at 5 kc (−1 db vs 0.0002 dyne per sq cm per cycle). Its directivity pattern is very broad but this can be controlled by using sufficient units in an array.

The starboard array consisted of six 5A hydrophones, one of which is shown in cross section in Figure 2. To provide the maximum signal-to-noise ratio, a two-stage coupling amplifier is included in the 5A hydrophone housing. The port array consisted of six 5B hydrophones. These differ from the 5A in that a transformer is used in place of an amplifier to provide a low-impedance output. The purpose of using two kinds of coupling was to determine the effect on the signal-to-noise ratio of running low-level leads from the hydrophone to the electric equipment. The use of an amplifier close to the crystals, although ideal from the standpoint of threshold noise, complicates the wiring and maintenance. It was thought that transformer coupling might be preferred, even if it meant extra shielding.

Circuits for Array. A block schematic diagram showing the elements of the electrically steered sonic system is given in Figure 3. This includes a switch which introduces variable delay between the third hydrophone on one side of the boat and the corresponding one on the other side, effectively making a two-unit array which may be steered under the boat. The spacing between these two hydrophones is approximately 30 inches, or the same as the fore and aft spacing of the six units for which the delay networks were primarily designed.

An array or line of hydrophones operates on the phase-cancellation principle. For instance, two hydrophones can be spaced to that when a plane sound wave of a given frequency ap-

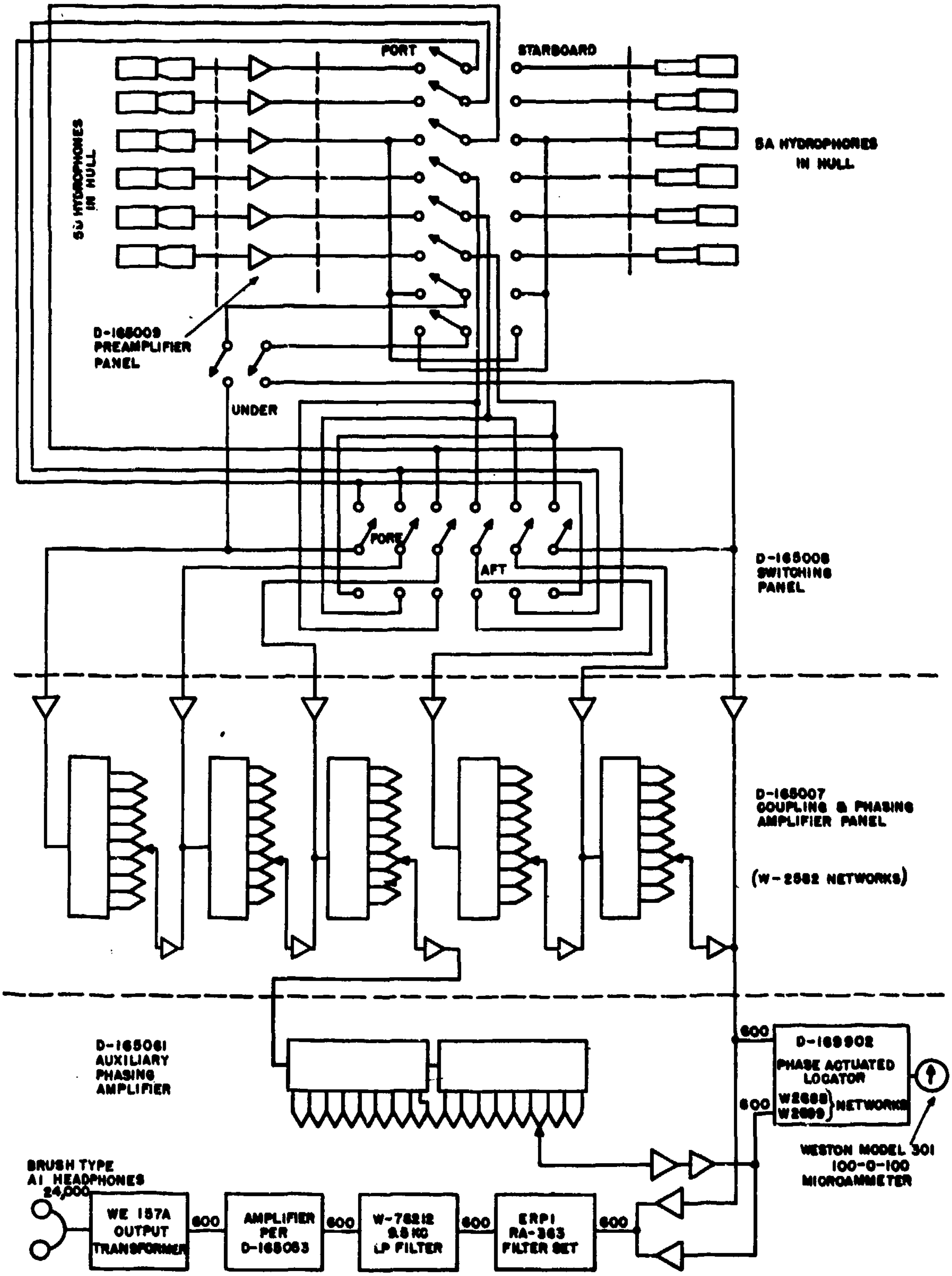


FIGURE 3. Electrically steered sonic listening equipment on *Elcobel.*

proaches along the line joining them, it reaches the second one at a maximum rarefaction of the medium at the same time that it reaches the first one at a maximum condensation. The two electric outputs are then 180 degrees out of phase and cancel completely where they are joined together. At any other angle of approach, the effect is less. If an electric network is inserted between the two outputs so that the first is delayed sufficiently to bring it into phase with the second, a maximum results instead of a null. Therefore, by using a variable delay network the beam pattern of the array can be steered over any desired angle.

The amount of phase shift α between adjacent hydrophones that is required to steer the directivity pattern of a line array over an angle of 90 degrees depends upon the factor $2\pi lf/c \sin \theta$, where l is the center-to-center spacing between hydrophones, f is the frequency, c is the velocity of propagation in the medium, and θ is the angle with respect to the direction normal to the line. Near normal incidence the magnitude of phase shift is almost linear with respect to θ, but as the angle θ approaches 90 degrees a small phase shift corresponds to a much larger change in θ. Changes in propagation velocity also have a greater effect on the accuracy as the angle approaches 90 degrees. In the circuit to be described, the phase delay is varied by the resistance potentiometer method. The five potentiometers are on a common shaft that is driven through helical gearing with a 4-to-1 reduction by a crank shown on the front of the panel.

The additional delay required to bring the output of one-half of the array into phase with the output of the other half for use with a

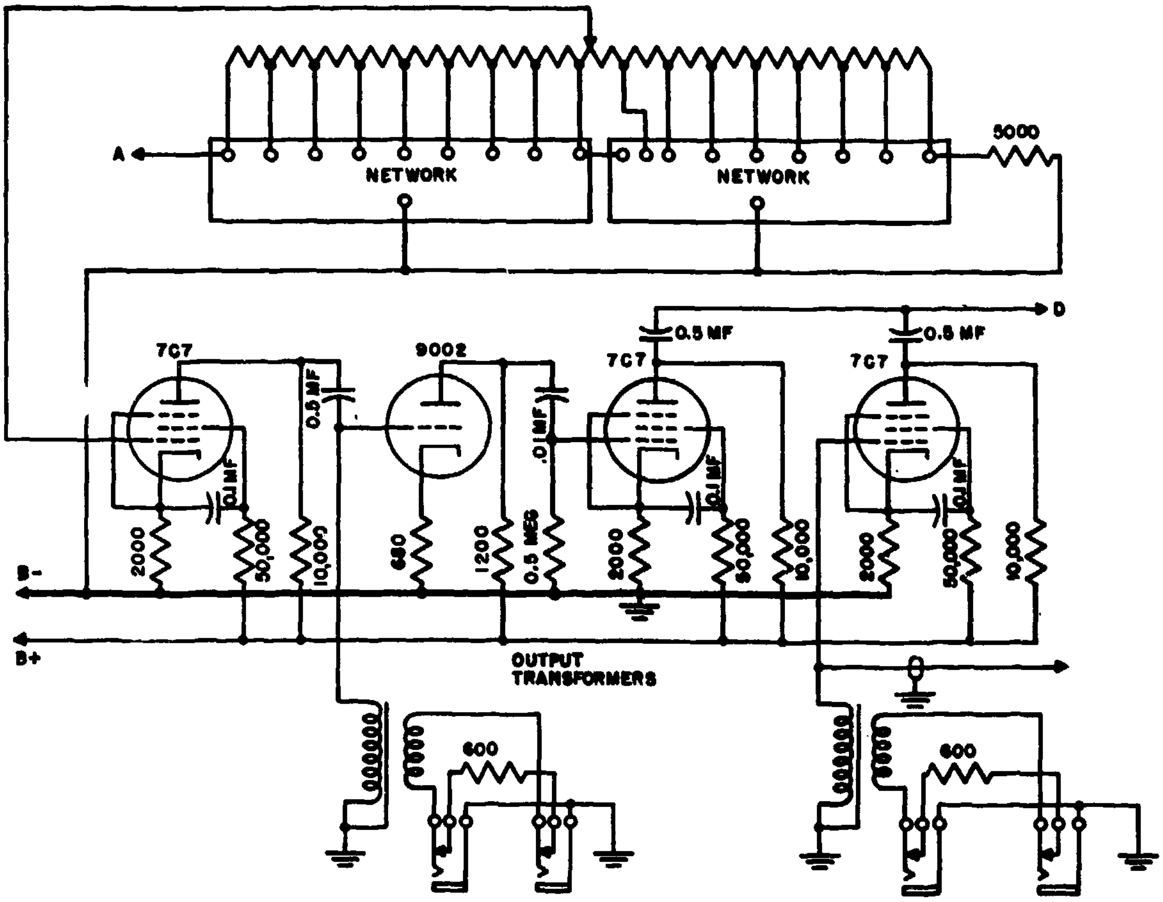


FIGURE 4. Schematic diagram of auxiliary phasing amplifier.

phase-operated left and right indicator system is provided by an auxiliary panel (coded D-165061) whose schematic diagram is shown in Figure 4. The operation of the *phase-actuated locator* [PAL] and *right-left indicator* [RLI] systems is discussed in Chapter 6.

In an array of hydrophones the loss variations of the several networks in tandem are added together, and when the variation from one end to the other is integrated over the frequency range from 1 to 10 kc for all the hydrophones of the array, no inequality is noticeable to the ear.

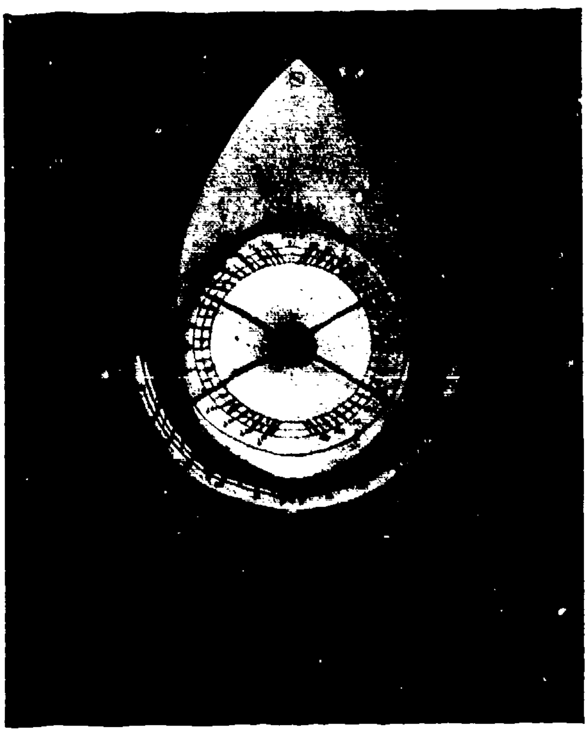


FIGURE 5. Front panel assembly of coupling and phasing amplifier.

Figure 5 is a photograph of the front panel assembly of the coupling and phasing amplifier. The four pointers shown in the photograph turn with a scissor-like motion so that with no delay the starboard pair coincide and the port pair coincide. As the delay is increased, one pointer on each side moves up and one moves down simultaneously.

The handwheel under the dial varies all five networks simultaneously. When the keys on the switching panel are thrown to fore and starboard, the upper right-hand quadrant is illuminated. The arm covering this quadrant moves from the vertical to the horizontal position as the handwheel is turned clockwise, the delay changes from 100 per cent to 0 per cent, and the lobe of maximum response is swept from dead ahead to abeam. To go past abeam, the key is thrown to aft. This illuminates the after quadrant, the hydrophones are reversed with respect to the delay and, when the handwheel is turned counterclockwise, the delay changes from 0 per cent to 100 per cent and the lobe of maximum response moves aft. The four indicating arms are arranged so that their angular displacement with respect to either axis is always the same. Therefore, when switching from one quadrant to another, the angular change can be made as small or as large as desired. This is useful in making a rapid survey of the four quadrants to insure that the loudest response is within the quadrant under examination. It is also useful in determining whether a target is dead ahead, since by throwing the key between port and starboard it can be observed when the target crosses the bow.

MEASURED CHARACTERISTICS

Frequency Response. The frequency response of the electrically steered sonic system is shown in Figure 6 in terms of the power into a 600-

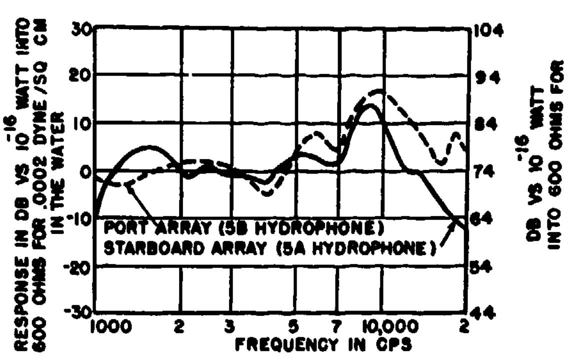


FIGURE 6. Frequency response of electrically steered sonic listening system.

ohm load at the output terminals of the phasing amplifier versus the sound pressure in the water at the location of the hydrophones. The scale is cross-referenced in terms of 0.0002 and 1 dyne

per sq cm per cycle. The latter is the present standard and is included on all drawings involving pressure-spectrum level. The response below 1 kc is not shown, since it was found by means of the variable filters that most of the noise caused by local sources close to the hull and by vibration which passed through the isolating mounts could be eliminated by including a 1-kc high-pass filter in the circuit. Although there are some differences in the response of the two types of hydrophone, they do not affect the impression gained by listening over the range from 1 to 10 kc. The same may be said of the effect of the hull on frequency response. There was found to be little difference in the response of the starboard array mounted in the hull and that of the same array mounted in a free sound field, except at high frequencies (above 8 kc) where the free-field response was about 10 db higher. The uniformity of the hydrophones as shown by individual free-field response curves is an important factor in maintaining the directive properties of the arrays. Any uncontrolled resonances within the listening frequency band caused by structural deficiencies would result in phase shifts between units which would upset the artificial phase relations established by the networks. Indicator circuits such as the PAL are particularly sensitive to such uncontrolled phase changes.

Directivity Patterns. The change in the response of a hydrophone or array of hydrophones as it is rotated in the sound field produced by a fixed source some distance away is commonly measured at single frequencies. Directivity patterns obtained in this way are used to confirm design computations and to check uniformity of product. They give a rather diffuse picture of what to expect when listening with the device, since listening is done with a band of frequencies and the effect cannot be described by a single-frequency pattern. This is particularly true in the sonic range where the listening bandwidth is much wider in octaves than a supersonic listening band of the same width in kilocycles.

The patterns presented in this report were measured with a band of thermal noise as the source. This is not completely descriptive either, as the ear may exercise its sense of pitch to discriminate, at least between high and low frequencies. It is well known that a listener may concentrate, just as if he were inserting a high-pass filter, on the higher frequencies whose sharper beam enables him to get a more accurate bearing, after he has used the overall loudness to locate the sound source. For this reason some of the patterns are shown for two noise bands, one for the high frequencies and one for the overall band, to give some idea of the type of pattern available for bearing determination by listening alone.

The directivity patterns of the electrically steered sonic array are given in Figure 7. The

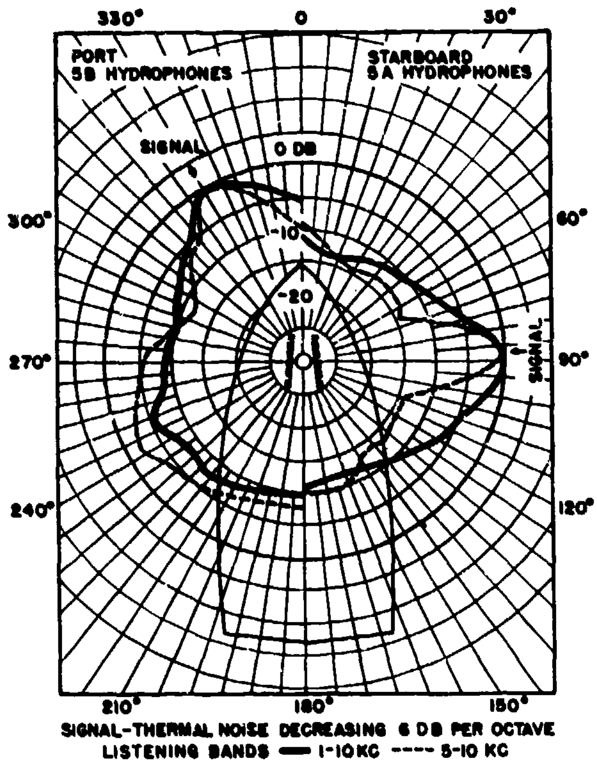


FIGURE 7. Directivity patterns of electrically steered sonic system; signal from fixed sources during electric rotation.

chart is in two halves, one for a signal coming from the starboard beam and the other for a signal coming from the port bow. Several characteristics of hull-mounted arrays are illustrated by these patterns. One is the blunting of the lobe as it moves away from abeam. This is a characteristic of electric steering and is due to the cumulative effect of departures from an

exact linear relation between phase shift and frequency. The lobe at 330 degrees would actually be broader if it were not for the effect of the boat hull which tends to reduce the response near the bow. Another characteristic is the sharpening of the main lobe by restricting the bandwidth to the upper end of the spectrum. This makes for greater bearing accuracy but has the disadvantage of increasing the amplitude of the minor lobes. This is a characteristic of all arrays. Reducing the wavelength results in narrower lobes which, however, occur more frequently, the pattern eventually repeating itself at decreasing angular separations.

The effect of the boat hull has been obtained by measurements on the *Elcobel*, as shown in Figure 8. The hull provides shielding between

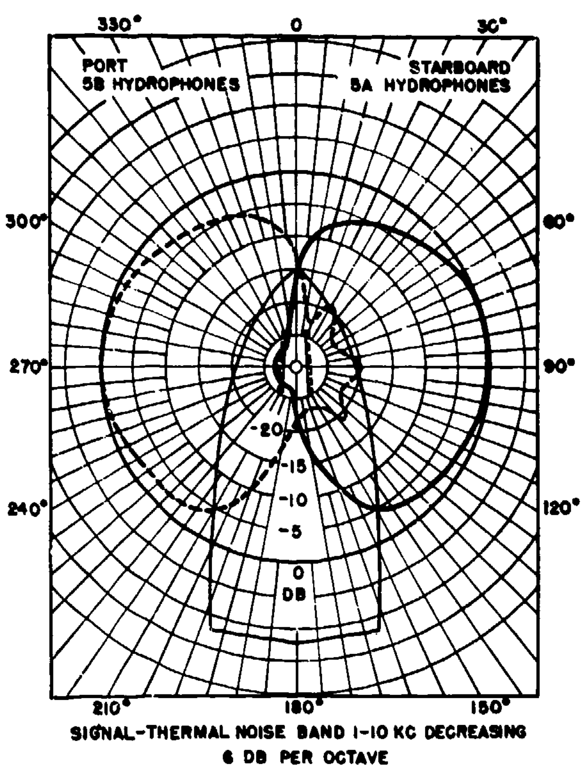


FIGURE 8. Effect of hull on electrically steered sonic system.

port and starboard in the order of 20 db or more for the sonic range. This is one of the advantages that comes with hull mounting and plays a part in deciding the location of sound gear on any type of boat. The loss due to grazing incidence at the fore and aft positions is a serious disadvantage. It not only reduces the sensitivity at those positions but causes a loss in signal-to-noise ratio because the directivity index does not change appreciably with angle of train.

The directivity index is a ratio of the volume enclosed by the directivity pattern, treated as a solid of revolution about the appropriate axis, to that of the sphere with radius of maximum

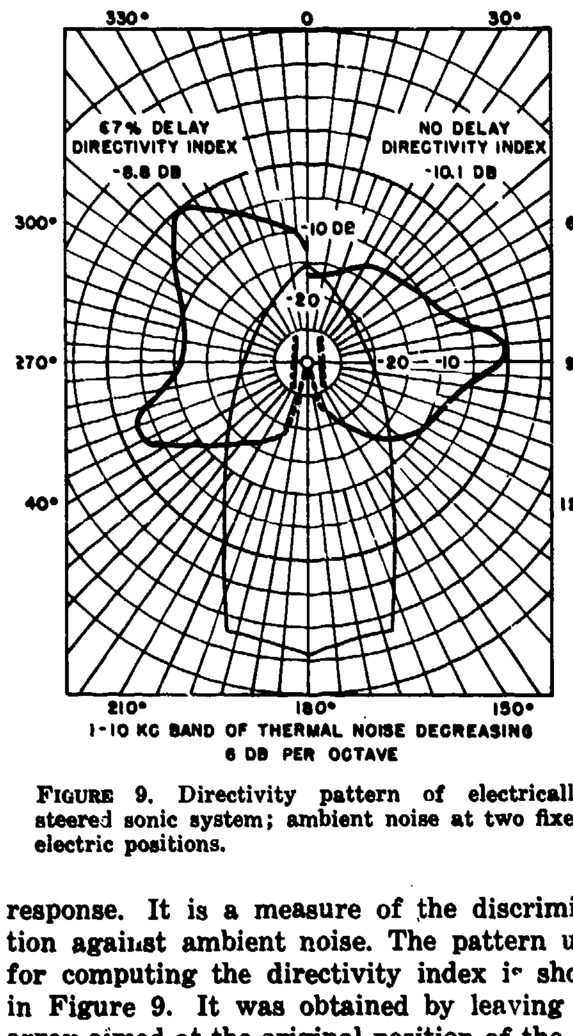


FIGURE 9. Directivity pattern of electrically steered sonic system; ambient noise at two fixed electric positions.

response. It is a measure of the discrimination against ambient noise. The pattern used for computing the directivity index is shown in Figure 9. It was obtained by leaving the array aimed at the original position of the signal and then moving the signal around the boat to simulate random noise. As shown in Figure 7, the loss incurred at the bow and stern may cause a side lobe to exceed the main lobe in intensity. This may lead to ambiguity, as by steering near the bow on a signal which is actually in the aft quadrant. For this reason it is necessary to scan all four quadrants to

locate all possible sources of interference before obtaining a bearing. For antisubmarine work this is not a serious disadvantage

The combined effects of hull mounting and electric steering are shown in Figure 10. This presents a pattern for each of the four com-

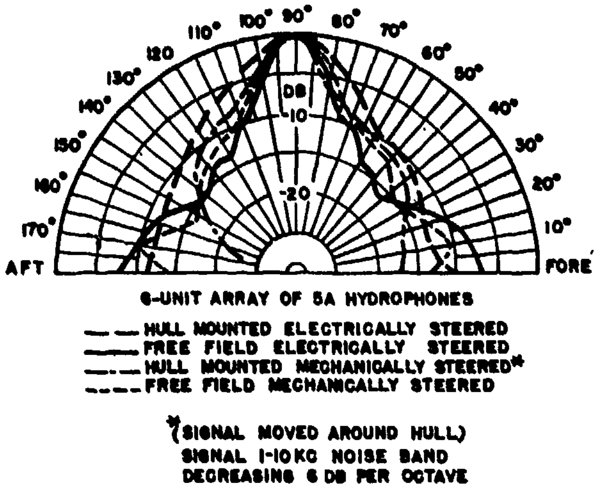


FIGURE 10. Directivity pattern showing combined effect of hull mounting and electric steering.

binations of hull versus free field and mechanical versus electrical steering. The basic pattern is that for a mechanically steered array in a free field. When the array is mounted in a hull but still steered mechanically, the pattern shows a slight broadening of the main lobe and the characteristic loss fore and aft. If the array is left in a free field and steered electrically, there is a slight narrowing in the main lobe but, principally, a broadening of the side lobes at the end points. The combination of hull mounting and electric steering gives a rather broad pattern with reduced side lobes. The effect of the hull may be likened to a tapered array, the taper being introduced by the successive losses caused by grazing incidence along the hull between hydrophones.

The patterns obtained by steering the two-unit array under the boat would be rather poor, characteristic of a two-unit array with wide spacing. However such an array used with the PAL circuit and a broad frequency band provides a good indication of bearing in the absence of secondary targets.

Another directivity pattern of interest is that showing the effect of projecting the hydrophones from the hull. Computations had indicated a considerable improvement to be expected by moving the hydrophones out from the hull. This improvement is due to the fact that the direct and reflected waves at the boundary of the water and lower impedance medium (the boat hull) are 180 degrees out of phase. As the hydrophone is moved away from the boundary, the phase difference becomes less, and instead of a loss there may be a gain in sound pressure.

Self-Noise. The spectra of self-noise with the boat underway for three speeds are given in Figure 11. These show the self-noise varying inversely with frequency more rapidly than is the case with ambient noise, which indicates that the higher frequencies are more suitable for listening while underway.

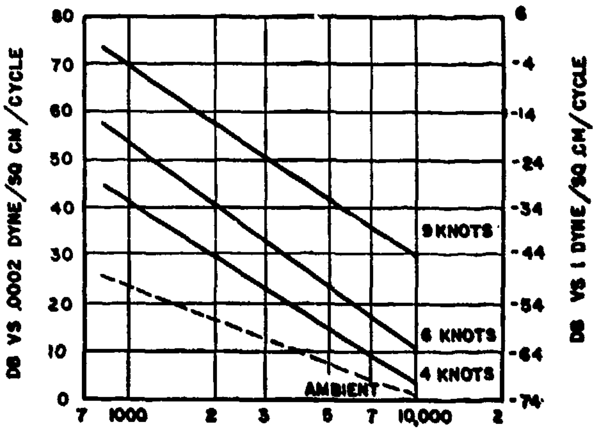


FIGURE 11. Self-noise spectra of electrically steered system (No. 1 sea) in terms of equivalent sound pressure at hydrophones.

Self-noise is a combination of noises from at least three sources. One of these is propeller cavitation. Another is engine vibration transmitted either directly through the hull or from the hull to the water and thence to the hydrophone. The underwater engine exhaust may also contribute to this. Third source of self-noise is the action of the water against the hull and hydrophone. When the boat is underway, this noise increases. The proper method of determining the effect of each source is to measure each independently. For instance, the effect of maintaining engine speed corresponding to a 4-knot water speed without motion through the water shows that at the upper end of the spectrum engine noise disappears into

the ambient but at the low frequencies its effect is important.

Isolation of propeller noise is more difficult to accomplish. Measurements made with hydrophones under the *Elcobel* trained on the propellers indicate that the slope of the spectrum is about 5 db per decade. This is in good agreement with measurements of ship's propellers reported elsewhere.[3] It is also necessary to take into account the effect of hull shielding which discriminates against the high frequencies.

To find the effect of motion through the water, tests were made with the boat in motion and with it tied to a dock while the engines and propellers were maintained at a speed corresponding to 9 knots. Such tests are more reliable as to slope than magnitude, since the level of propeller cavitation undoubtedly increases when the boat is restrained. They definitely indicate, however, that motion through the water is a heavy contributor to the low end of the spectrum.

With the isolation of propeller noise and the noise due to motion through the water, it is possible to break down the total noise spectra into their component noise sources. The result is given in Figure 12 for two boat speeds. These analyses are based on two requirements for the component spectra: one, that they conform in slope to the considerations discussed above and, two, that they add up on a power basis to the total noise curve as measured. These curves which, for lack of precise information, have been drawn as straight lines indicate that for the sonic arrays the controlling noise is due to motion through the water. The upper end of the frequency band departs least from the ambient noise for the existing sea conditions, and at low speed such departure is due almost entirely to noise from the propellers.

A streamlined cover over the six-unit array was tried. Over the listening band up to 10 kc, the cover does not offer much improvement. At low speeds, there is a small decrease in the self-noise, but at higher speeds it increases. Confirmation of this was obtained in connection with self-noise measurements on the electrically steered supersonic arrays discussed in the next section. These arrays were located directly forward of the six-unit arrays. It was observed that the self-noise picked up by the supersonic arrays when they were steered aft was considerably higher when the cover was on the six-unit arrays.

Internal Noise. Internal noise is defined as the noise introduced in the listening system by the electric equipment. Basically, it is the thermal noise in the resistive component of the impedance at the lowest-level point of the circuit. Other noise sources may predominate, however, particularly noise in the amplifier tube immediately following the low-level point. This is commonly referred back to the input of the tube as the series grid resistance whose thermal noise would produce an equivalent level at the output. In an array the threshold is lower, since the active area of sound pickup is increased without changing the effective resistance at the low-level point. Internal noise spectra for hydrophone systems in this report

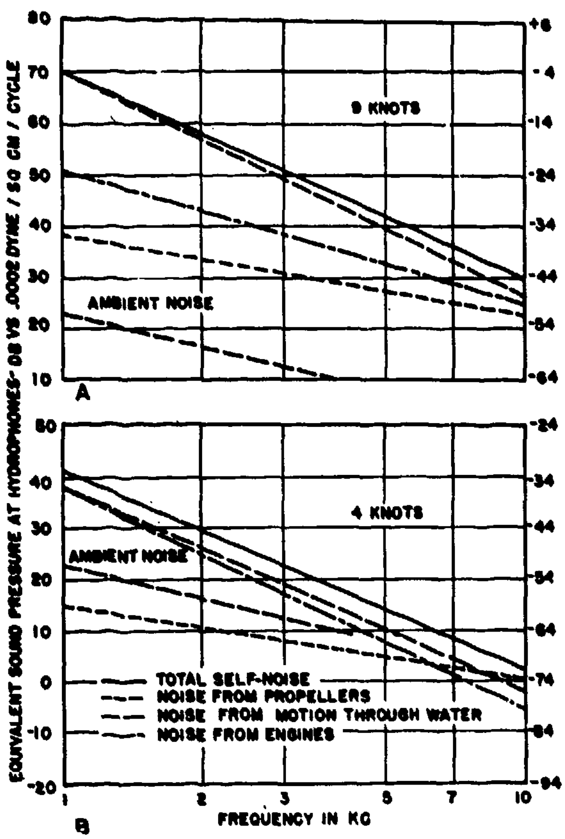


FIGURE 12. Analyses of self-noise of electrically steered sonic system; No. 1 sea.

are given in terms of the sound pressure in the water which would produce the same voltage as the observed circuit noise. The spectrum for the internal noise of the electrically steered sonic system is shown in Figure 13.

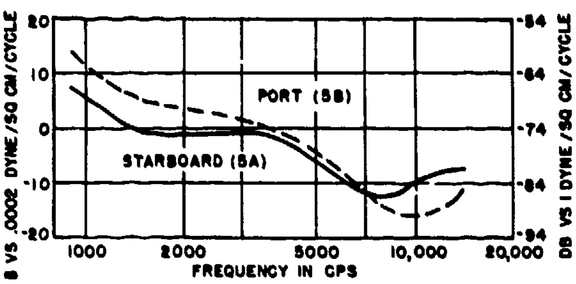


FIGURE 13. Internal noise spectra of electrically steered sonic system in terms of equivalent sound pressure at hydrophones.

4.3 THE ELECTRICALLY STEERED SUPERSONIC SYSTEM

The need for investigating supersonic listening systems is clearly indicated by the frequency spectra of self-noise with the boat underway (Figure 12) and also the rather broad directivity patterns associated with sonic frequencies. It is true that any beam width can be obtained for any frequency range by using a sufficient number of hydrophones and spacing them properly. At the low sonic frequencies, sharp beam patterns with low side lobes can be obtained only by using an array whose dimensions approximate the length of the boat. The characteristics of a 3-foot, sonic array showed that the region above 5 kc is better suited to bearing determination by listening than the lower frequencies.

Although supersonic frequencies are attractive both from the standpoint of the reduction of self-noise and of the increase of directivity obtainable with small-sized units, there are several factors to keep in mind. The attenuation of sound energy in water increases with frequency very rapidly beyond 20 kc. The difference between 5 kc and 20 kc is small compared with the reduction in self-noise and the improvement in directivity obtainable when size is a determining factor. The results obtainable by listening above 30 kc were not investigated in this study. The type of signal being detected is another factor. Ship propellers turning above cavitational speeds are rich in supersonics. Below cavitational speed, which may be as high as 6 knots for a submarine at 300 feet, supersonic frequencies are reduced some 40 db. The ability of a submarine employing evasive tactics to maneuver at reasonable depths without creating high-frequency noise makes its detection by listening from a small boat underway very difficult.

HYDROPHONES AND CIRCUITS

Hydrophones. The supersonic arrays consisted of two Type 7A assemblies of Rochelle salt crystal hydrophones. The details of the construction are shown in Figure 14. As the

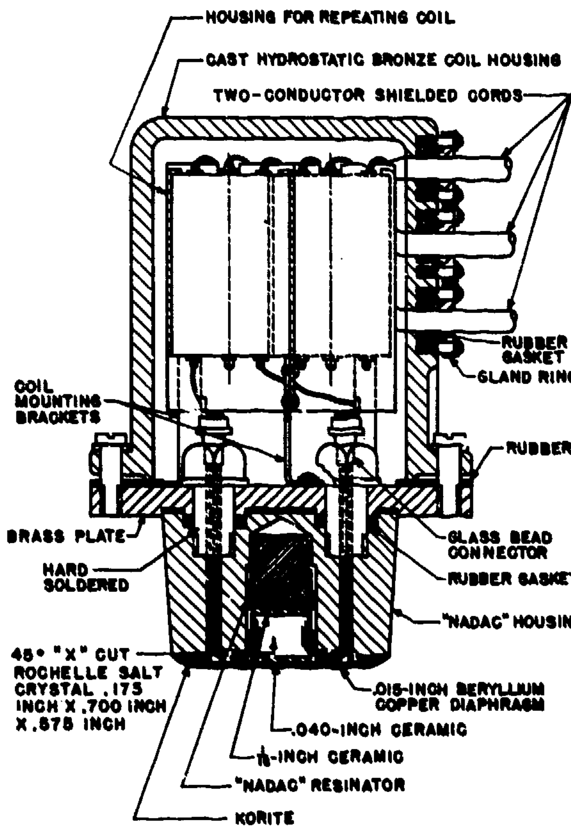


FIGURE 14. Cross section of 7A hydrophone electrically steered supersonic system.

result of experience with the 5A-type hydrophones, no protective cover was used with these arrays. However, an attempt was made to reduce the hull effect by framing the array

with a 1/4-inch brass plate which extended for several wavelengths fore and aft of the unit. The use of metal instead of wood in the hull should considerably reduce the attenuation of the sound wave at grazing incidence.

Electric System. The amplifier and phasing system used with the supersonic arrays is similar to the sonic system shown in Figure 3. In this case, no attempt was made to steer the array under the boat on account of the wide spacing. The leads from each of the nine elements were brought to their own coupling amplifier from which they passed through successive phase networks. A block of networks is used to bring the two halves of the arrays (omitting the ninth unit) into the PAL circuit as before.

The listening system makes use of the output from all nine units and a heterodyne system is used to bring the frequency band from the supersonic range down to the audible range. A 1-kc high-pass filter is included to prevent l-f noise from overloading the heterodyne system.

Measured Characteristics

Frequency Response. The overall frequency response of the supersonic system is shown in Figure 15. This response is fairly uniform over

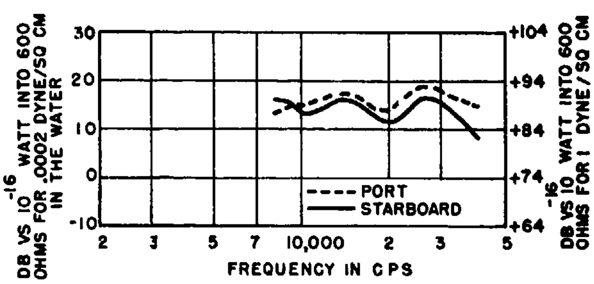


FIGURE 15. Frequency response of electrically steered supersonic system measured at output of phasing amplifier.

a broad band of frequencies. However, there are limitations to its usefulness outside a certain range. At the low frequencies, the directivity becomes poor. At the upper end of the band, there is a resonance around 26 kc between the crystal capacity and the transformer. As the location of this resonance differed among units, the listening range was restricted to the band from 13 to 23 kc.

Directivity Patterns. The directivity patterns obtained with a band of thermal noise decreasing 6 db per octave are given in Figure 16. The patterns are for two angles of incidence as the array is steered electrically through the signal. Comparison with similar patterns in

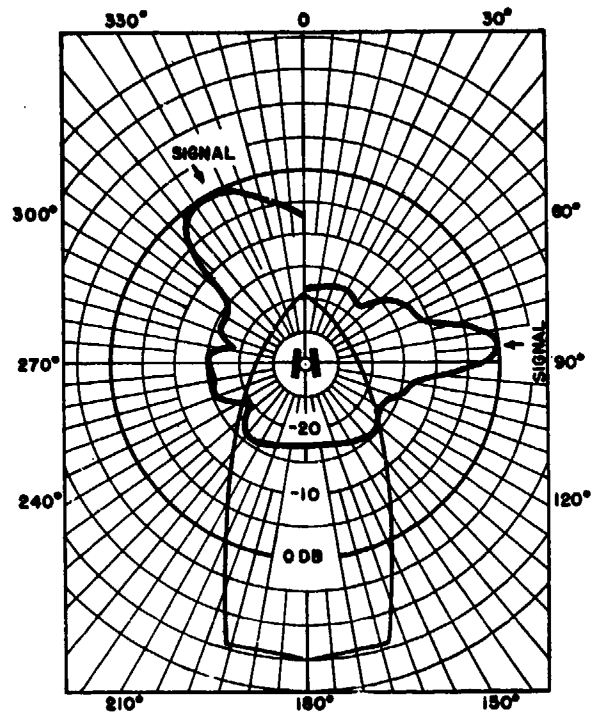


FIGURE 16. Directivity pattern of electrically steered supersonic system; signal from fixed sources during electric rotation.

Figure 7 shows a considerable improvement in the beam width and particularly in side lobe reduction due to the greater number of elements. There is no need to divide the band into two parts because the octave range is small and also because the 10-kc band selected by the modulator is reduced to 5 kc for listening.

The directivity index versus frequency is shown in Figure 17. The effect of the hull on the sound level reaching the hydrophone is shown in Figure 18. The per cent of the circumference over which the effect is small has been increased as compared with that obtained with the sonic arrays (Figure 8). This has been enhanced by the brass plate surrounding the 7A hydrophone. It effectively substitutes a high-impedance for a low-impedance reflector

in the vicinity of the units, thereby avoiding phase cancellation along the reflector. The effect is now one of summation which varies somewhat with the angle of train as shown by the

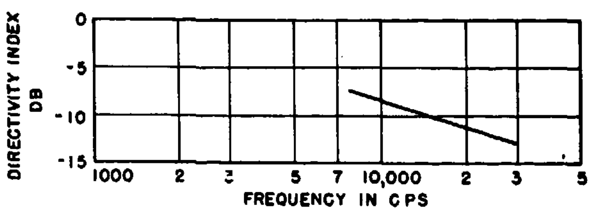


FIGURE 17. Directivity index of 7A hydrophone.

irregularities in the pattern. This method is effective only at frequencies for which the wavelength is small, since the reflector must extend beyond the hydrophones for several wavelengths to be of any use.

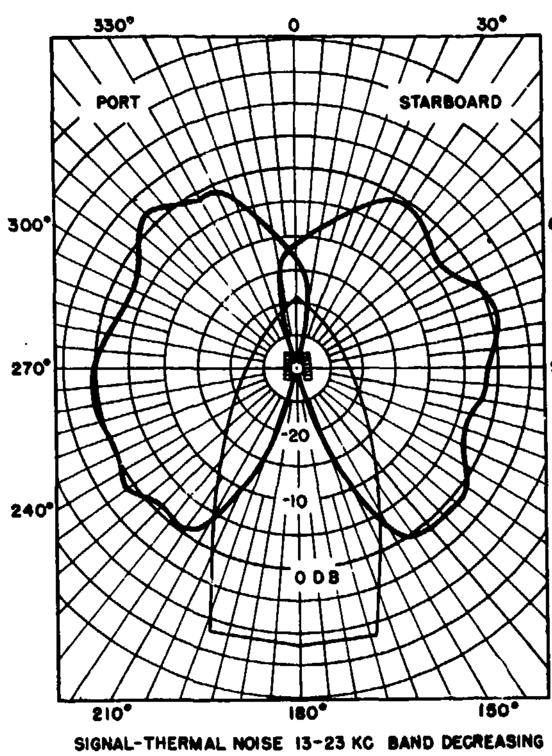


FIGURE 18. Effect of hull on listening with the 7A hydrophones.

Self-Noise and Internal Noise. The noise produced in the supersonic arrays steered abeam when the boat is underway was measured at 4, 6, and 9 knots. At the low speeds the level of self-noise is so close to ambient that an analysis is not justified. This leaves only the 9-knot speed to be broken down into its components, as shown in Figure 19. The noise caused by motion through the water plays a minor role at supersonic frequencies. The main contribution is from the propellers except at the lower end

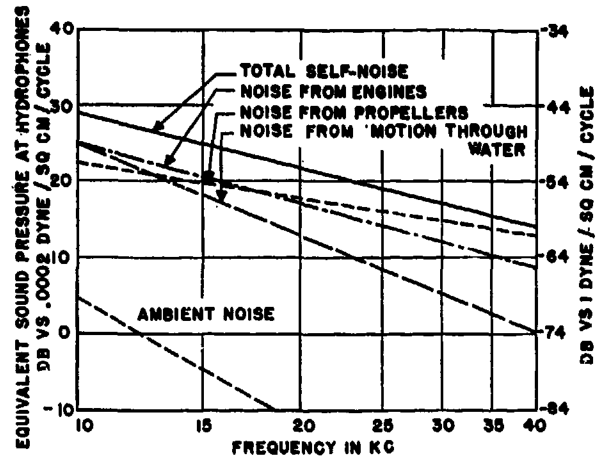


FIGURE 19. Analysis of self-noise at 9 knots of electrically steered supersonic system.

of the spectrum. The propeller noise spectrum is a continuation of that used for the sonic range, and, as in the sonic range, it depends primarily on the shielding effect of the hull.

4.4 THE MECHANICALLY STEERED SONIC SYSTEM

The principal disadvantage of the electrically steered sonic arrays tested is the relatively poor directivity which, because of the effect of the boat hull, leaves a sector of uncertain bearing accuracy about 20 degrees either side of the bow and stern. Electric steering also presents difficulties in design and construction which make it inherently expensive. These disadvantages can be avoided to a large extent by using a similar array suspended below the boat and steered mechanically. The greater depth at which such an array would operate is a further advantage. The effect of the hull is not completely eliminated and for extreme accuracy must be taken into account.

Hydrophone and Circuits

A hydrophone, coded 9AA, was made up using six inertia-type, permanent-magnet units

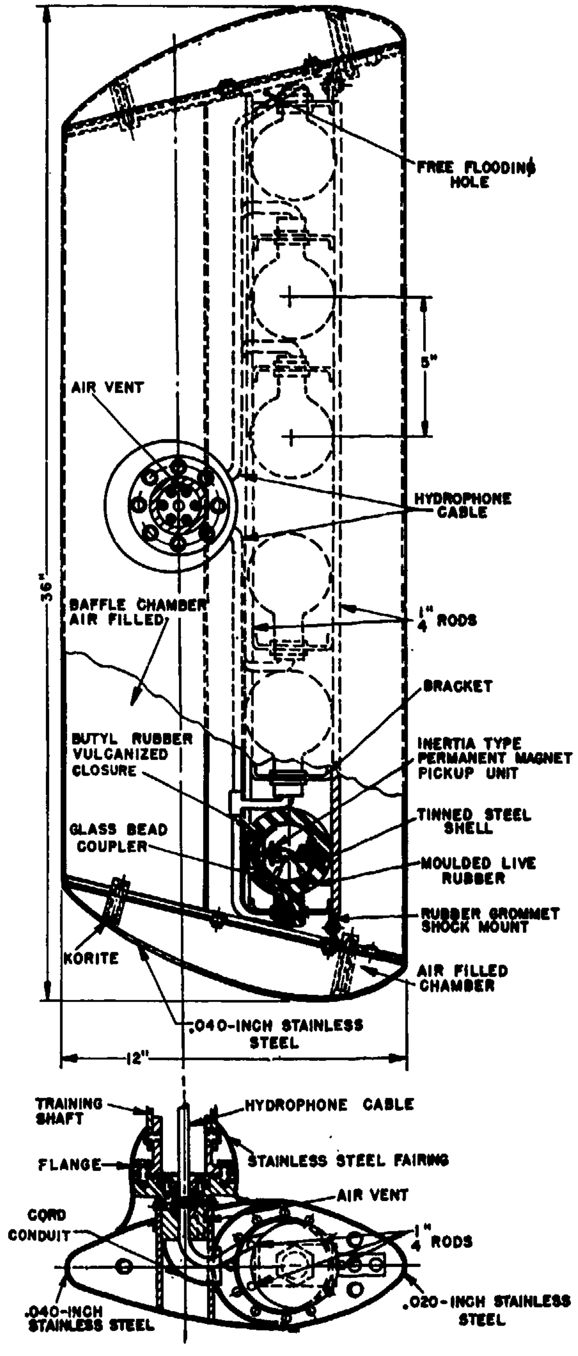


Figure 20. Cross section of 9AA hydrophone; mechanically steered sonic system.

spaced 5 inches apart. This unit provided a directivity pattern with a considerable reduction in the rear response. A mechanism for raising and lowering the array and for training it on the target was installed.

The 9AA hydrophone is shown in cross section in Figure 20. The six units were mounted on a frame which held them in a water-filled chamber making up the front section of a wing-shaped stainless-steel body. The rear section was air-filled to serve as a baffle for reducing the rear response. The directivity pattern of each unit is useful in this application to avoid the effects of reflections from the rear wall of the front chamber as well as to reduce the rear response of the assembly. The end pieces of the body were also air-filled to reduce the side response. A photograph of the hydrophone in place under the starboard side of the *Elcobel* is shown in Figure 21.

Figure 21. 9AA hydrophone mounted on starboard hull of *Elcobel*.

The principle of operation of the inertia unit is simple. An armature is suspended over the pole pieces of an electro magnet by a flat spring member. The magnet is mounted on the inside of a steel sphere. Motion of the sphere is communicated to the magnet which causes the armature to move. Relative motion between the armature and the magnet alters the magnetic field and induces a current in the winding. The natural period of the mass of the armature and the stiffness of the spring member is about 1,000 c. The steel shell and the magnet resonate near 10 kc. These resonances can be shifted and

broadened by the use of mechanical damping in the form of rubber mounted in the air gap.

A block diagram of the electronic equipment used with the mechanically steered sonic array or 9AA hydrophone is shown in Figure 22.

to match effectively each unit to the input circuit at the low end of the frequency range in order to obtain a more uniform frequency response. The frequency responses of the individual units showed uniformity not only over

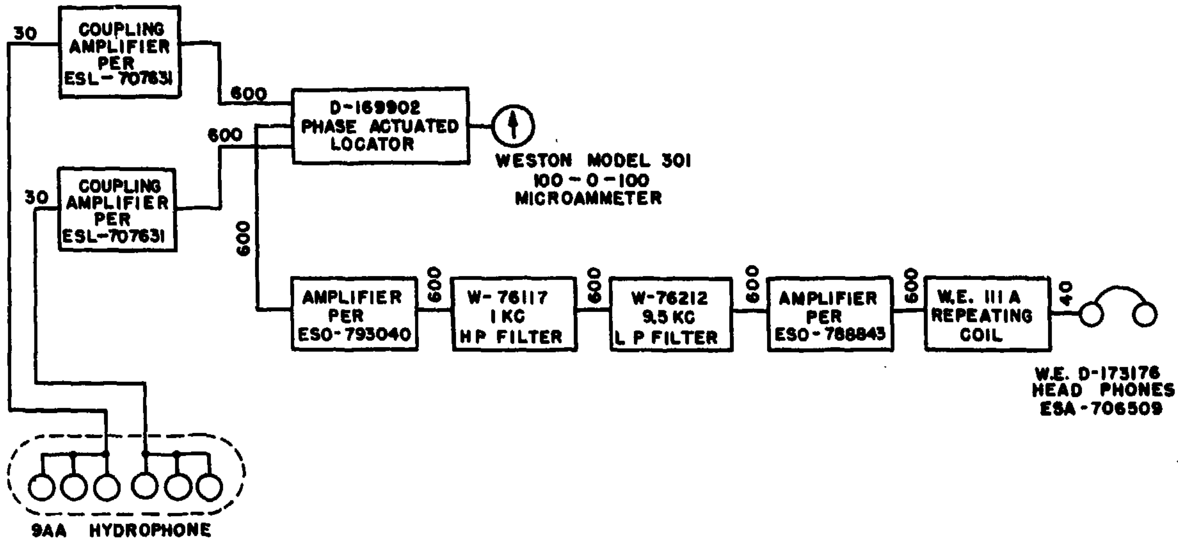


FIGURE 22. Block diagram of mechanically steered sonic system.

MEASURED CHARACTERISTICS

Frequency Response. The frequency response of the 9AA hydrophone is shown in Figure 23 for 0-degree and 180-degree incidence of the sound wave. It will be seen that the voltage

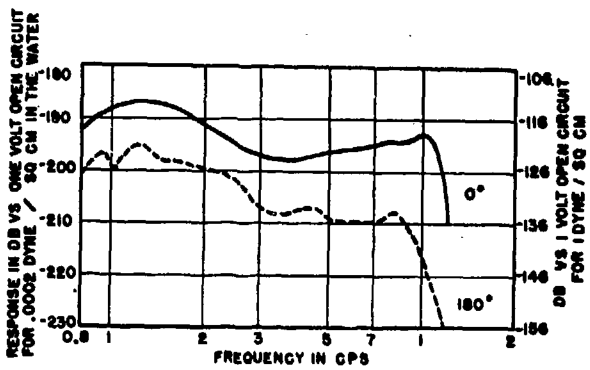


FIGURE 23. Frequency response of mechanically steered six-unit sonic array.

developed for a sound pressure of 0.0002 dyne per sq cm is relatively small. This is primarily due to the low impedance of the six units in parallel. The parallel connection was used so as

the frequency range but among the units, which is an advantage for the use of phase-operated left and right indicator systems.

Directivity Patterns. The directivity patterns for the 9AA hydrophone were measured in two ways, at a lake test station using a band of noise with a slope characteristic of ship sounds and on the *Elcobel* using a band of noise with uniform response over the spectrum. The uniform frequency band places more emphasis on the high frequencies, resulting in a narrower beam width as shown by the patterns in Figure 24. The directivity index for the 9AA hydrophone is plotted as a function of the frequency in Figure 25.

Self-Noise. The self-noise of the 9AA hydrophone is shown in Figure 26. The directivity patterns of self-noise at two speeds, shown in Figure 27, differ in appearance from patterns of the hull-mounted systems. The patterns bulge out toward the rear by the amount of shielding provided by the baffle and are essentially an indication of how this shielding varies with angle of train. It was observed that at high speed, the noise level in the water is higher

for the hull-mounted arrays abeam and lower fore and aft. This is due to the proximity of the bow wave and to the hull shielding, and ties in with the conclusion reached earlier that motion through the water is the controlling noise source for the hull-mounted sonic arrays. This part of the band is, therefore, seriously restricted in the level of signal which can be distinguished above the internal noise. The noise level at the lower end of the band is not a limiting factor because self-noise and ambient noise are more likely to be controlling.

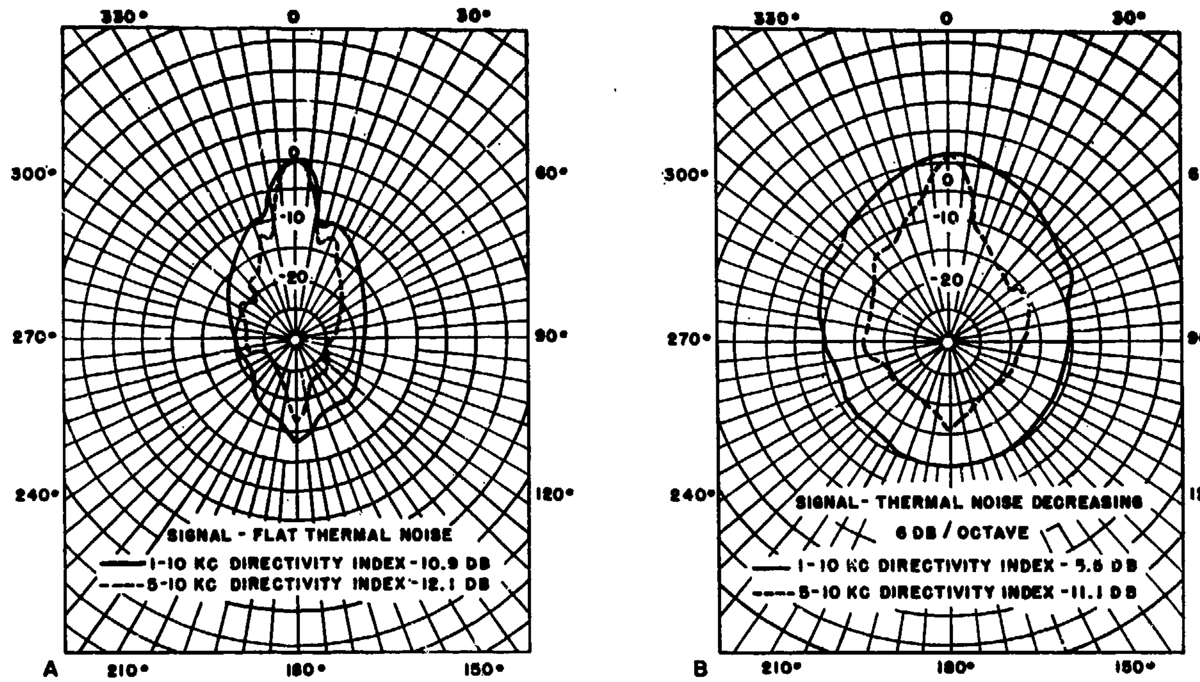


FIGURE 24. Directivity patterns of mechanically steered sonic system measured using different signals.

Internal Noise. The threshold noise for the 9AA hydrophone, as compared to that for the hull-mounted sonic arrays, indicates a serious

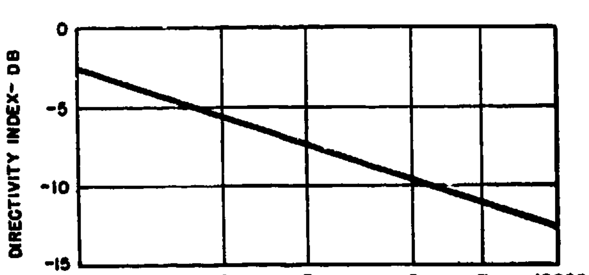


FIGURE 25. Directivity index of 9AA hydrophone.

deficiency of the 9AA in this respect. At the upper end of the frequency band, the noise threshold of the 9AA is 20 to 30 db higher.

4.5 THE MECHANICALLY STEERED SUPERSONIC SYSTEM

The same advantages apply to the use of a mechanically steered supersonic system as to a sonic system, namely, the elimination of the boat-hull interference as it affects the azimuth coverage and the removal of the complication of electric steering. Since a supersonic frequency band provides good directivity with a hydrophone of small size, a unit with an active face smaller than that of the 7A array operating at a somewhat higher-frequency range was designed. This unit was later developed into the No. 6 series of hydrophones and projectors.

HYDROPHONE, DOME, AND CIRCUIT

As originally designed for this system, the No. 6 type hydrophone discriminated against

signals coming from the rear of about 30 db. It was thought that this could be improved by using a baffle in a streamlined dome, which at the same time would eliminate cavitation and turbulence due to motion through the water

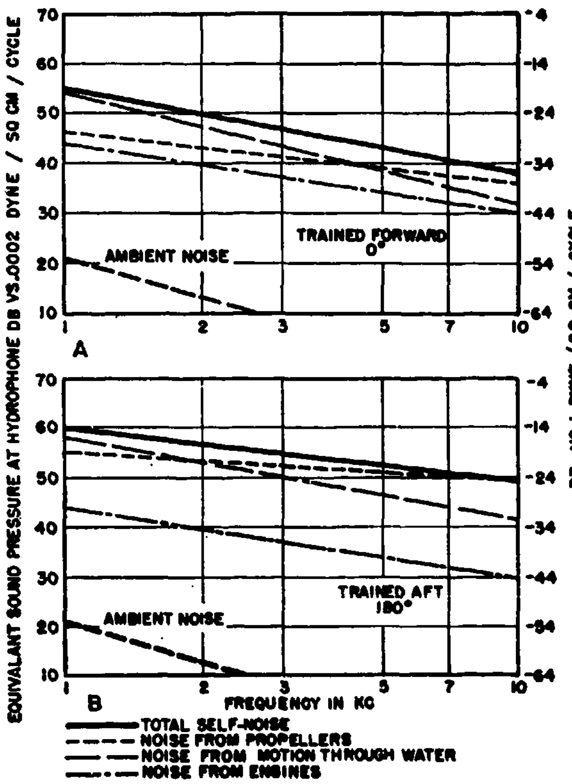


FIGURE 26. Self-noise of 9AA hydrophone installation.

at moderate speeds. The 6C hydrophone which was finally employed in the dome is shown in cross section in Figure 28.

A half-sized model of the QBF dome was built to include a castor oil filled baffle. The steel casting of the baffle was later covered with ¼-inch cork rubber to improve its shielding. The stainless-steel acoustic window was not only half-sized but half the thickness of that used in the QBF dome, 0.010 inch instead of 0.020 inch. Since this dome was completely submerged, a top section similar to the bottom section was added and provided with a flange. A block diagram of the circuit used with the 6C hydrophone is shown in Figure 29.

MEASURED CHARACTERISTICS

Frequency Response. The 6C hydrophone has a broad frequency range extending from below 10 kc to beyond 60 kc. The region from 20 to 30 kc was selected for high efficiency and satisfactory beam width, but listening could be done above and below this range if desired. However, the effect of the dome on frequencies above 35 kc was not investigated and, therefore, the operation of the phase sensitive PAL circuit was confined to the 20- to 30-kc band.

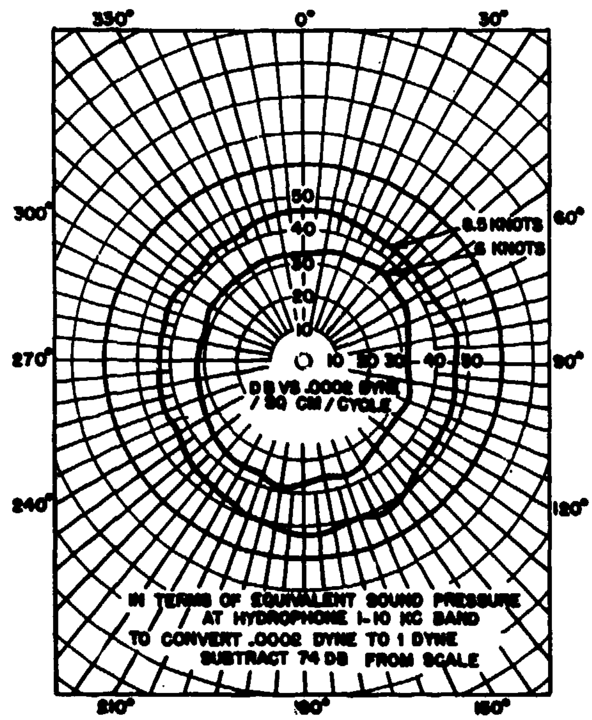


FIGURE 27. Directivity patterns of self-noise of mechanically steered 9AA hydrophone.

Directivity Patterns. The directivity patterns shown in Figure 30 illustrate the effect of the dome. The 57-degree beam width is not so narrow as that of the supersonic array but gives a fairly good indication of bearing with very little interference from side lobes. At 330 degrees a side lobe appears which is entirely due to specular reflection from the acoustic window. The function of the baffle is twofold. Its primary purpose is to shield the hydrophone from the rear. It also provides absorption inside the dome chamber for multiple reflections

which would seriously distort the directivity patterns.

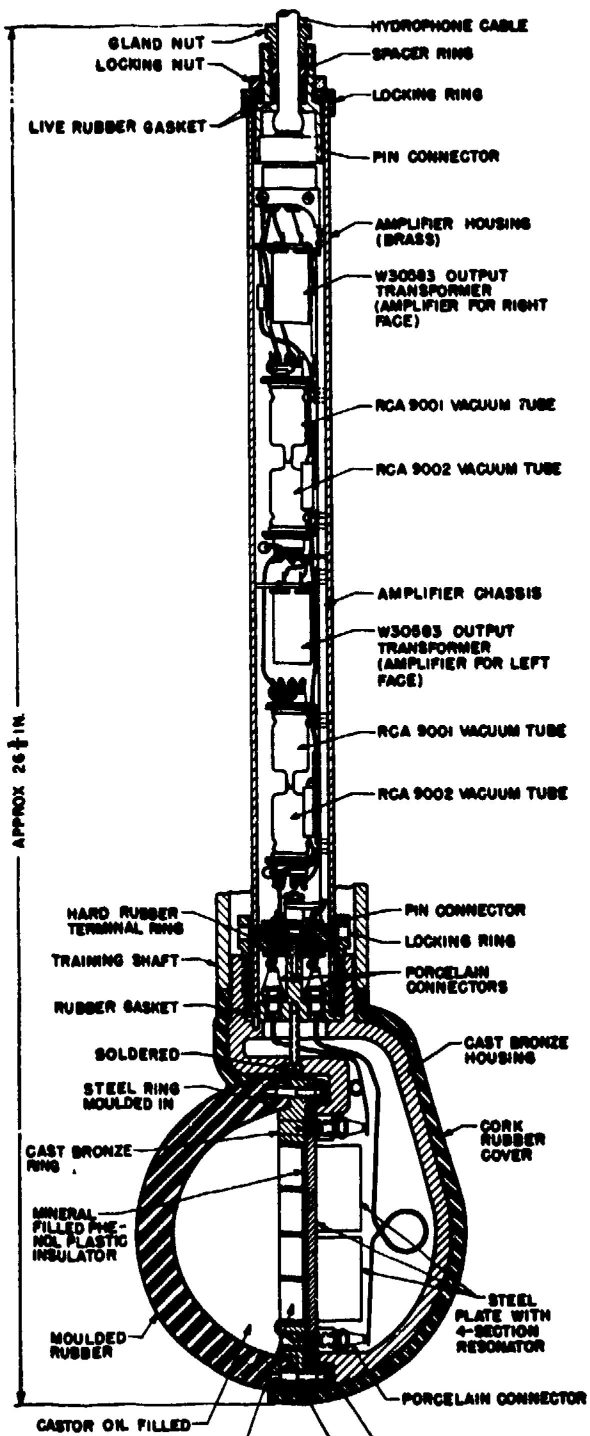


FIGURE 28. Cross section of 6C hydrophone; mechanically steered supersonic system.

The effect on the directivity pattern of the cork-rubber cover placed over the back of the 6C hydrophone is shown in Figure 31. This was measured without the dome and shows a considerable reduction in rear response which is valuable in reducing the effect of a nearby noise source such as the propellers. In applying the cork rubber, the sides of the hydrophone appeared to be most important, and the greatest improvement was obtained by bringing the cork rubber as far forward as possible without shielding the crystal face.

Self-Noise. The frequency spectra of self-noise measured with the hydrophone trained forward are shown in Figure 32. The steep slope of these spectra is caused by the frequency discrimination of the baffle. The difference between the front and back response of the 6C hydrophone also contributes to the slope of the self-noise spectra, although its effects are somewhat confused by reflections within the dome. It is interesting to note that the absolute levels of self-noise are several decibels higher than those obtained with the hull-mounted 7A hydrophones (Figure 19). However, by using a hydrophone in the dome with a beam width comparable to that of the 7A, the self-noise level is reduced.

4.6 THE THROUGH-THE-HULL SONIC LISTENING SYSTEM

RESPONSE CHARACTERISTICS

A production-type JP-1 through-the-hull system was installed on the *Elcobel* to serve as a basis for comparison with the several experimental systems already described. This system is a mechanically steered sonic system using a 3-foot line hydrophone capable of responding to frequencies over the entire sonic and the lower supersonic regions. Included in the system was an amplifier whose frequency characteristic could be varied by means of a series of filters. A resonant circuit (bass boost) was also available to raise the response in the region of 100 c for special listening conditions. The frequency response of the amplifier is shown in Figure 33.

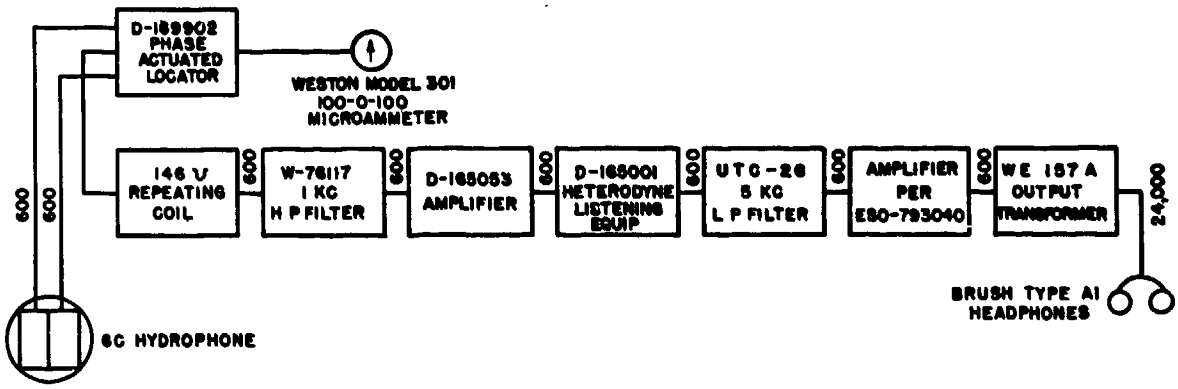


FIGURE 29. Block diagram of circuit for the 6C hydrophone.

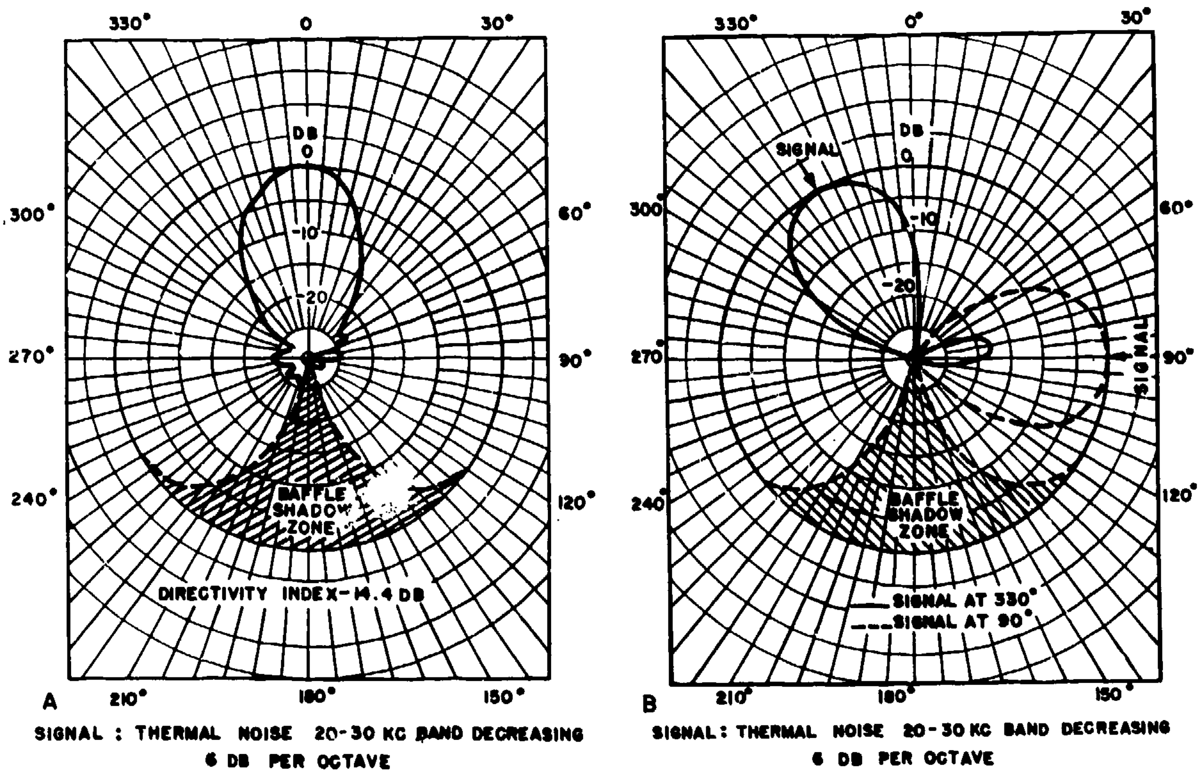


FIGURE 30. Directivity patterns of 6C hydrophone in 25-inch dome.

Directivity Patterns

The directivity patterns of the JP-1 hydrophone were measured in two ways as in the case of the 9AA hydrophone. The results of these measurements are shown in Figure 34. The difference in patterns between the 1- to 10-kc band and the 5- to 10-kc band is very much less than it was for the 9AA hydrophone (Figure 24). This is caused by the comparative lack of low-frequency response which would otherwise broaden the pattern when included. If it is considered necessary to use the lower frequencies to detect particular types of signals, these may be emphasized by means of low-pass filters or the bass boost.

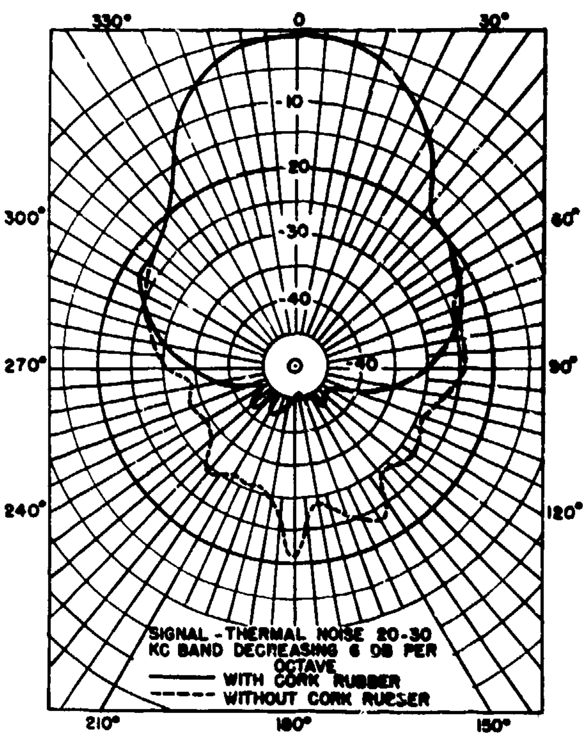


FIGURE 31. Directivity pattern of 6C hydrophone with and without cork-rubber back.

Self-Noise and Internal Noise

The JP-1 hydrophone, due to its unshielded magnetic circuit, is very susceptible to electric interference produced by the engine ignition system. For this reason, self-noise underway is essentially nondirectional. At 6 knots the interference completely masks the propeller noise, even when the hydrophone is aimed

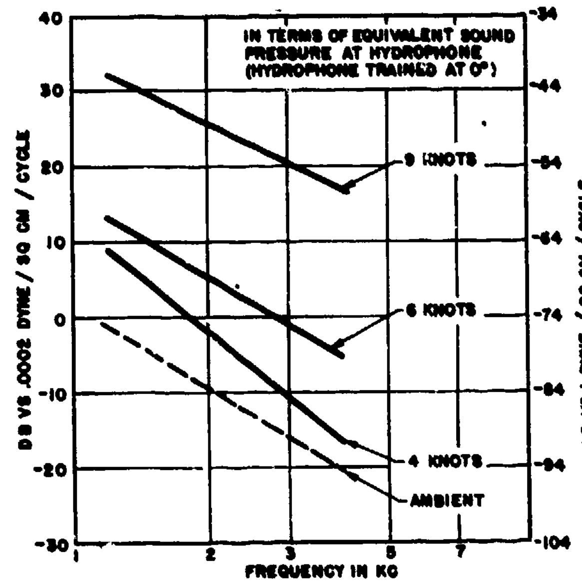


FIGURE 32. Self-noise spectrum of 6C hydrophone in dome; No. ½ sea.

astern. At 9 knots only the rear shows the effect of the propellers above the noise from electric interference.

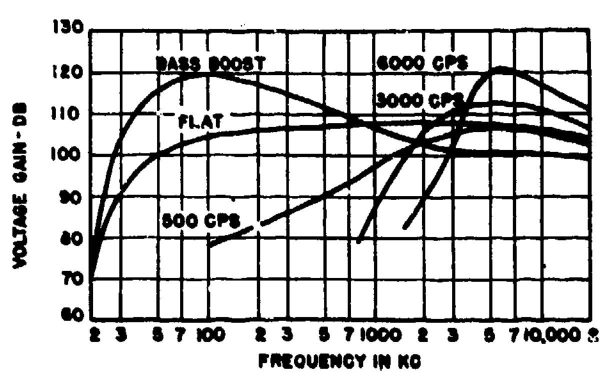


FIGURE 33. Frequency response of amplifier for through-the-hull equipment.

The internal noise threshold of the JP-1 hydrophone is approximately 7 db better at the upper end of the sonic frequency range than that of the 9AA hydrophone.

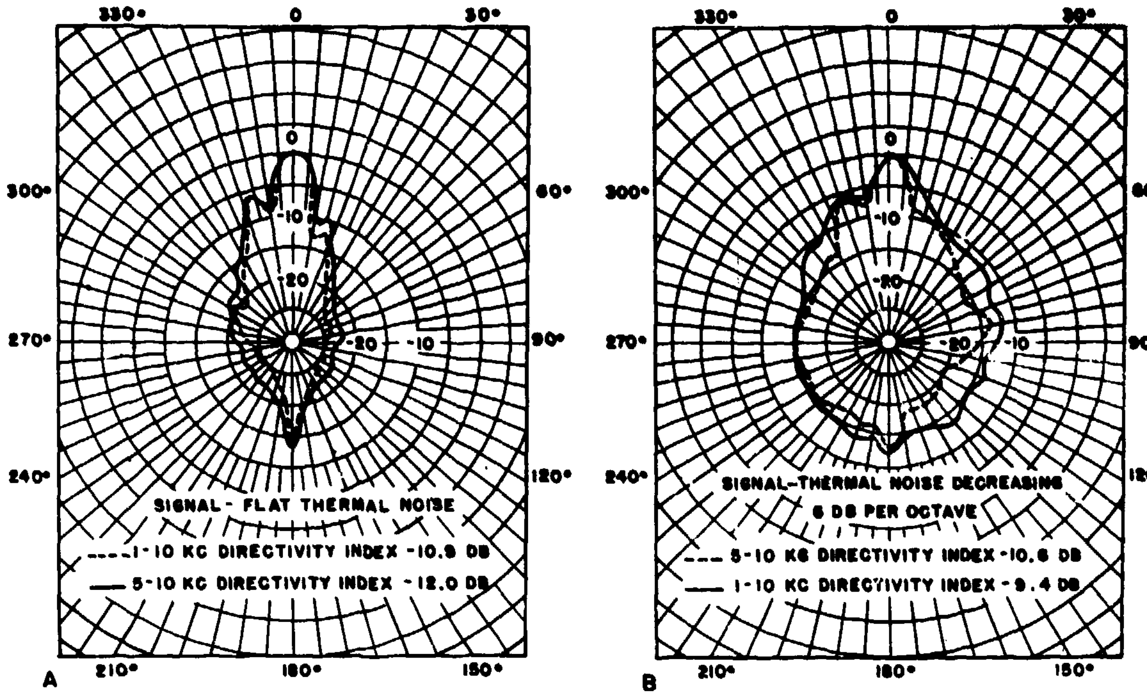


FIGURE 34. Directivity patterns of JP-1 hydrophone; measured using different signals.

Chapter 5

COMPARISON OF EXPERIMENTAL SYSTEMS

IT IS NOW PROPOSED to evaluate the characteristics of the four listening systems on the *Elcobel* and to evolve in the process a set of criteria by means of which they and listening systems in general may be compared.[a] These characteristics are, to a certain extent, interlinked. The importance to be attached to each is a matter of judgment and depends on the environment in which they are to be used. The internal noise threshold, for instance, is unimportant in a heavy sea where ambient and self-noise are high. Some characteristics not evaluated in this study are also important, such as the ultimte cost, size and weight, ruggedness, effect on the maneuverability of the boat, and ease of maintenance.

5.1 COMPARISON OF MEASURED CHARACTERISTICS

Beam Width and Side Lobe Reduction

Taking up each characteristic in turn, it is apparent first that beam width and side lobe reduction are closely correlated. Beam width is defined as the angle intercepted by the main lobe at 10 db down from the maximum. Side lobe reduction is measured by the number of decibels the highest side lobe is down from the main lobe. Considered only for its effect on the listener, beam width has to do principally with the ease of obtaining a bearing. For a single target, a fairly wide beam, say ± 20 degrees, gives a reasonably accurate bearing indication. By sharpening the main lobe, this may be improved and the number of times it is necessary to train the beam through the target to obtain a bearing may thereby be reduced. However, by using a phase-operated left and right indicator system with a split hydrophone, the accuracy for a single target becomes practically independent of beam width.

In the presence of an interfering source of sound which is not random in direction, beam width again becomes important. The narrower the main lobe, the better the ability to separate two targets whose intensity difference at the hydrophone is less than the side lobe reduction. When the two targets are separated by an angle no greater than the maximum width of the main lobe, resolution may always be improved by decreasing the width of this lobe.

Frequency Response

The frequency response characteristic of a hydrophone system is important mainly for the indication it gives of uniformity and phase balance. A so-called flat response has no significance, since it may be altered elsewhere in the circuit as desired. The existence of a resonance in the listening band may not impair the quality of the received signal. It does, however, indicate rapid changes of phase which may upset the directivity patterns and the operation of left and right indicators, both of which depend on uniform phase relations across the face of the hydrophone.

Directivity Index

The directivity index affects the performance of a listening system because it is a measure of the discrimination against ambient noise. Since ambient noise is always present, the directivity index is one of the most significant characteristics of a listening system. The effect of the directivity index of all the systems on ambient noise level versus frequency in a No. 6 sea is given in Figure 1. The results indicate an increasing improvement in the ability to penetrate ambient noise as the frequency

[a] Those interested in comparisons between various listening systems might also see the report on submarine and surface craft listening equipment.[1] Here three submarine and two surface listening systems are given qualitative relative ratings on the basis of simultaneous runs on the same targets at sea. However, the factors contributing to the differences found between systems were not so completely investigated as in the work here described.

increases. This trend is carried over to the high-frequency instruments and constitutes a point in their favor. A No. 6 sea was used for

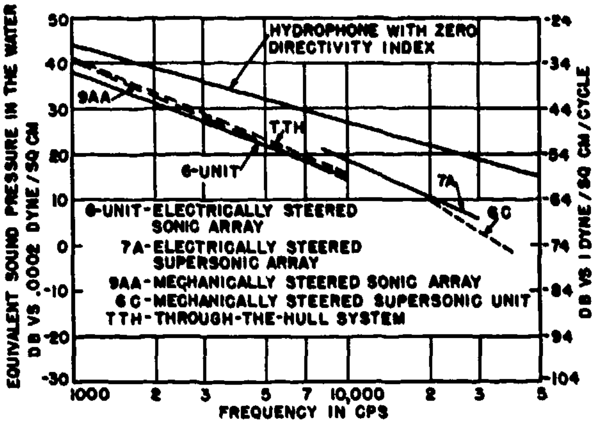


FIGURE 1. Effect of directivity index on ambient noise of random incidence.

this comparison because its noise level is sufficiently high to keep the output of all the systems above their internal noise thresholds.

INTERNAL NOISE

In order to compare the threshold curves of internal noise directly with ambient noise, they have been increased by their respective directivity indexes as shown in Figure 2. At any

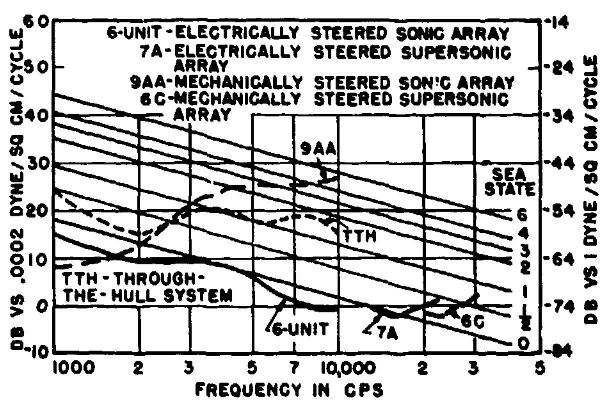


FIGURE 2. Internal noise in terms of equivalent ambient noise compared with ambient noise produced by various sea states.

frequency, the point where the system curve crosses a sea state curve, interpolated if necessary, defines its threshold in terms of the ambient noise. For example, it would be difficult to measure ambient noise with the through-the-hull system in less than a No. 1 sea in the band from 3 kc to 10 kc. The electrically steered sonic array is capable of measuring the noise of a zero sea.

SELF-NOISE

Another important characteristic of listening systems is self-noise both at rest and underway. It has been shown that hull-mounted sonic arrays are subject to self-noise with the boat at rest. In general, noises of this type which may be classified as hull microphonics have most effect on hydrophones mounted close to the hull and operating in the sonic frequency range. When the boat is under way, there are three primary noise sources—motion through the water, propeller noise, and engine vibration.

Relative signal-to-noise ratios have been plotted versus angle in Figure 3. At the 9-knot speed, the highest signal-to-noise ratio is pro-

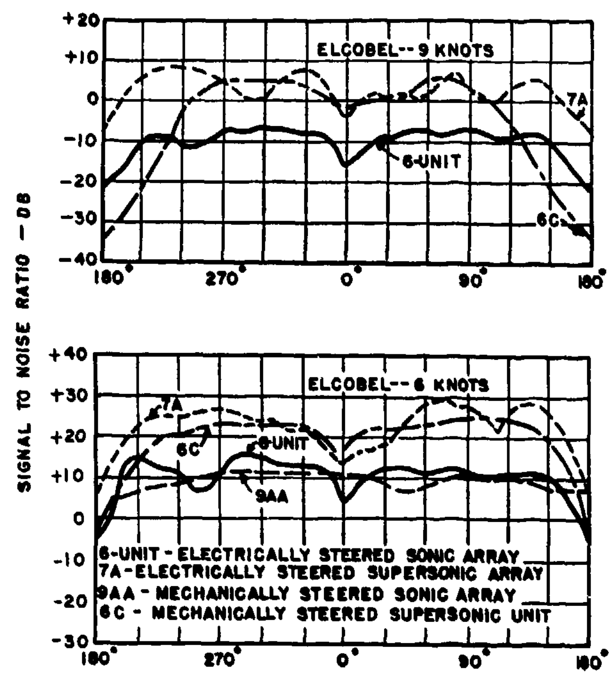


FIGURE 3. Relative signal-to-noise ratios of the different systems.

vided over most of the azimuth circle by the hull-mounted supersonic arrays. At the 6-knot speed, the systems show the same relative performance but with less difference among them.

In general, the supersonic systems are superior to the sonic from the standpoint of signal-to-noise ratio with the boat underway.

Rear Response

Rear response has been listed as one of the important attributes of a listening system. Its benefits, however, are limited to signals in that part of the azimuth circle in which there is no interfering noise source. As soon as the hydrophone is trained toward the propellers, there is a rapid deterioration of signal-to-noise ratio. The angle at which this occurs is a function of beam width, but for two hydrophones with the same beam width the signal-to-noise ratio can be maintained over a wider angle by using the boat hull as a shield against propeller noise.

System Ratings

On the basis of the above data and discussions, the qualitative system ratings are shown in the first part of Table 1. The estimates in the second part of the table are based on tests described in the following section.

5.2 COMPARISON OF SYSTEMS AT SEA

The sea tests were divided into the following classifications.

1. Bearing accuracy.
2. Listening range.
3. Effect of interference.
4. Ease of operation.

TABLE 1. Characteristics of listening systems on the *Elcobel*.

System	6-Unit	7A	9AA	6C	TTH
	A. Based on measured characteristics				
Beam width	Fair	Good	Good	Poor	Good
Side lobes	Poor	Fair	Good	Excellent	Good
Phase balance	Good	Good	Excellent	Excellent	Good
Directivity index	Good	Good	Good	Good	Good
Threshold	Excellent	Excellent	Poor	Good	Fair
Rear loss	Fair	Good	Fair	Good*	Fair
Self-noise					
Underway	Poor	Excellent	Good	Good	Poor
At rest	Fair	Excellent	Good	Excellent	Good
Azimuth coverage					
Underway	Fair	Good	Fair	Poor	Poor
At rest	Poor	Poor	Excellent	Fair	Excellent
Resolution	Fair	Good	Good	Poor	Good
	B. Based on sea tests				
Bearing accuracy	Good†	Good†	Excellent	Fair‡	Good
Observed range	Good‡	Good‡	Poor	Good‡	Excellent
Ease of marking	Good‡	Excellent‡	Excellent	Excellent‡	Good
Ease of operation (Section 7.5)					
Underway	Excellent	Excellent	Poor	Good	Fair
At rest	Excellent	Excellent	Fair	Good	Fair

* Excellent without dome.
† Within quadrants.
‡ Within the azimuth coverage limits.
TTH through-the-hull system.
6-Unit electrically steered sonic array.
7A electrically steered supersonic array.
9AA mechanically steered sonic array.
6C mechanically steered supersonic unit.

Most of the data were obtained with the *Elcobel* drifting and the engines turned off. Most of the work was done with the USNUSL test boat *Amada* as the target.

Bearing Accuracy and Listening Range

A summary of the bearing accuracy data for the five equipments is given in tabular form in Table 2. The bearing error is the difference

between the sound operator's bearing and the visual bearing obtained with the range finder. A good part of the data was obtained at very low signal levels. The level of the target was purposely kept low in order to obtain data on maximum listening ranges along with bearing accuracy. The short ranges also reduced the effect of thermal conditions.

TABLE 2. Bearing accuracy of *Elcobel* listening systems.

System		Average bearing error (degrees)	Standard deviation of bearing error (degrees)	Number of observations
TTH*		−1.1	1.76	529
9AA†		−1.0	1.45	222
6C‡		+0.1	2.17	250
6 Unit§			1.95	353
7A‖			1.83	306
By quadrants				
6 Unit	−1	−1.5	1.89	131
	2	+2.8	1.80	78
	3	−5.3	1.57	41
	4	+0.8	2.24	103
7A	1	0	1.71	123
	2	−2.7	1.90	68
	3	+1.0	1.54	47
	4	−0.7	2.13	68

* TTH through-the-hull system.
† 9AA mechanically steered sonic array.
‡ 6C mechanically steered supersonic unit.
§ 6-Unit electrically steered sonic array.
‖ 7A electrically steered supersonic array.

The *phase-actuated locator* [PAL] indicator does not remove the sources of error. Its function is primarily to assist the ear in obtaining a bearing and in this way to contribute to the overall accuracy. Some tests were made to evaluate this contribution. Using the electrically steered sonic array, 250 observations were made with and without the PAL. The difference in the distributions of error is shown in Figure 4. This shows the increase in the per cent of total errors below a given value obtained by using the PAL, indicating a much narrower error distribution. The observed maximum ranges for each system are averaged as follows:

System	Avg Max Range	Sea State
Through-the-hull	825	1
6-Unit electrically steered sonic	700	1
7A Electrically steered supersonic	800	1
Through-the-hull	680	2
6C Mechanically steered supersonic	600	2
9AA Mechanically steered sonic	400	2

(The shortness of these ranges is of course due to the purposely low level of the artificial target.)

In another series of tests, the ship noise of the *Amada* proceeding at 5 knots was used as

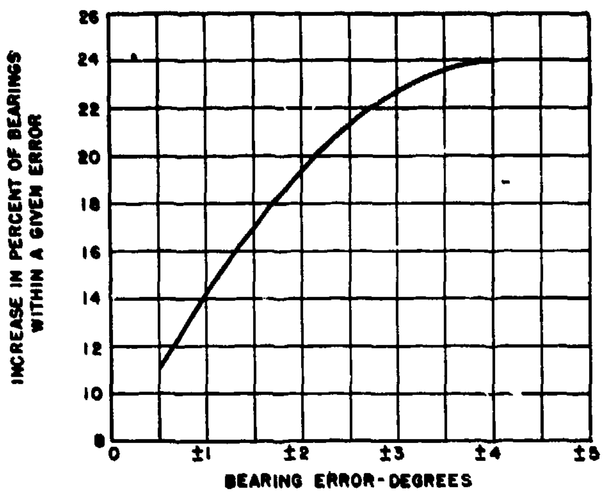


FIGURE 4. Improvement in bearing accuracy due to use of PAL indicator.

the target for listening from the *Elcobel* while the latter was underway. A plot of the maximum observed listening range for each system versus the speed of the *Elcobel* is shown in Figure 5.

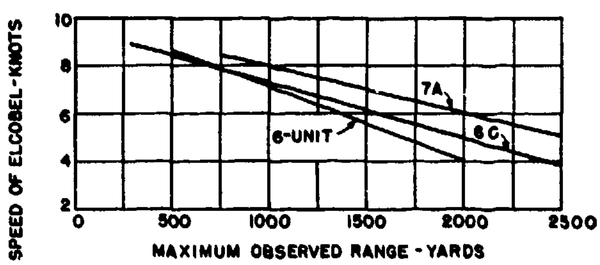


FIGURE 5. Maximum observed range versus speed; signal from *Amada* at 5 knots; No. 1 sea.

EFFECT OF INTERFERENCE

The effect of target interference on bearing accuracy was tested with the 9AA sonic system and the phase-operated left and right indicator system under sea conditions. The auxiliary *Decibel* supplied the artificial sound source and a second boat, the *Billie B*, produced the interference by running at a number of fixed angles between it and the *Decibel* with reference to

the listening boat, the *Elcobel.* The observers began to search for the target as soon as the interfering ship got under way. The bearings were recorded until the interference became so weak that there was no longer any doubt as to the location of the target ship. The two signals were sufficiently different in character so that the presence of the target could be detected soon after the interfering ship began its run.

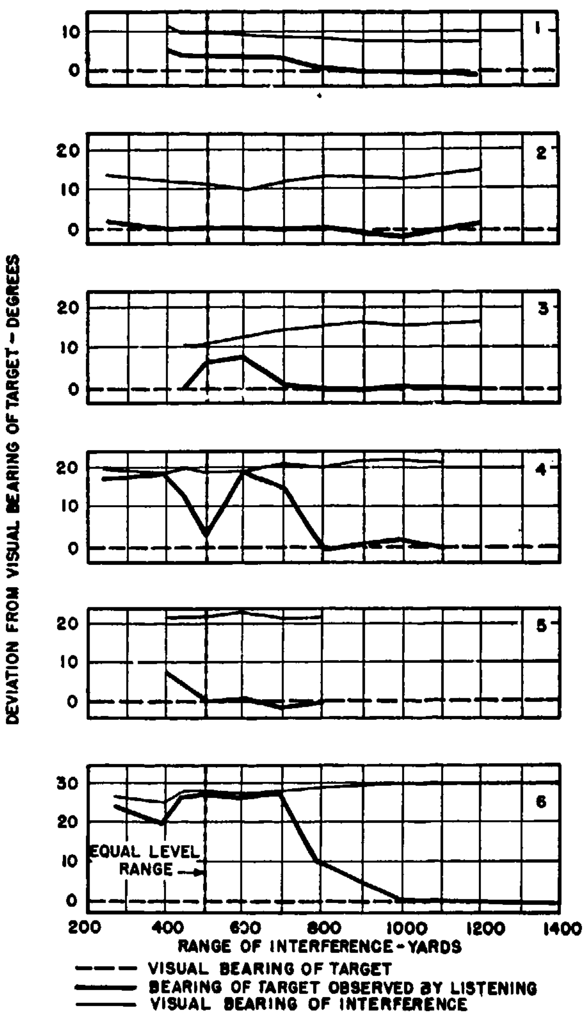


FIGURE 6. Resolution of target and interference using 9AA system.

A plot of the bearings obtained compared to the true location of the target and of the interfering ship is given in Figure 6. Four runs are shown with the true locations of the target and interference as determined by visual bearings and the apparent location of the target as obtained with the 9AA systems. The levels of the interference and the target were equal at about 500 yards. In general, large bearing errors were observed when the level of the interference was equal to or greater than that of the target. With the exception of runs 2 and 5 the level of the interference decreased about 4 db before the observer was sure of the target.

EASE OF OPERATION

The relative ease of obtaining a bearing with the five different systems is determined by two factors. One is the physical effort required to train the hydrophone. The other is the type of

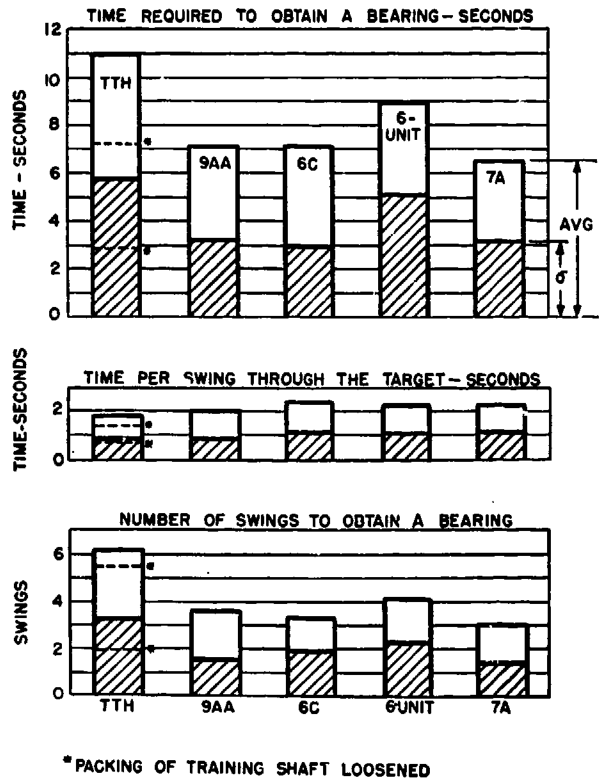


FIGURE 7. Time involved in obtaining a bearing.

indicator provided to tell the observer when he is on the target. In spite of differences between the systems, there was no appreciable difference in the time (about 2 seconds) taken by the observers using the phase-operated bearing indicator to swing through the target. Any difference came in the number of times it was found necessary to do so, as shown in Figure 7.

5.3 CONCLUSIONS AND RECOMMENDATIONS

The chief requirement for any underwater listening system is maximum range with sufficient bearing accuracy. All other features have a relative importance according to their contribution to this primary objective. The maximum observed range depends on the relative levels of signal and noise delivered to the observer and on his ability to distinguish between them.

Only the signal level is completely outside the control of the system designer. The water noise picked up with the signal can be reduced by making the transducer directional. Depending on the frequency band, a limit for transducer directivity is reached either in the size of transducer required or in the beam width, which becomes so narrow that a target cannot be found. The internal noise of the transducer reaches a physical limit set by thermal agitation in the resistive component of its impedance. The electric circuit has the same limitation with noise added by amplifier tubes and interference. Self-noise, which increases rapidly as the boat gets underway, can be controlled by placing the transducer so as to shield it from the propellers and by shaping it or providing a dome so as to reduce local turbulence. Since self-noise usually originates at certain parts of the hull, the directivity of the transducer also plays a part.

With this general background the following specific recommendations for listening systems on small patrol craft can be made on the basis of the experience with such systems on the *Elcobel.*

Hydrophone

The hydrophones should be free from uncontrolled resonances in the listening band and should be divided into two symmetrical halves, each at least 3 wavelengths across at the upper frequency limit, for use with a phase-operated left and right indicator system. Sufficient vertical directivity should be included to provide an overall directivity index in the order of −15 db. From the standpoint of self-noise, supersonic frequencies are best, but it is recognized that longer ranges may be obtained at sonic frequencies. For the detection of submarines using evasive tactics, it may be of advantage to listen to frequencies below 1 kc, although the value of such detection is reduced by lack of directivity and high noise levels. If only one frequency band can be made available, the region from 5 to 10 kc heterodyned to a band below 5 kc is recommended.

Training Mechanism

To obtain the greatest azimuth coverage with the greatest accuracy for a fixed maximum hydrophone dimension, a mechanically steered transducer is recommended. If it is desired to use electric steering with hydrophone mounted in the hull, the frequency band should not extend below 10 kc as self-noise becomes excessive. In such cases also, the location of the hydrophones should be carefully selected to minimize hull interference with the signal and to obtain as much shielding from the propellers as possible.

Bearing Indicator

Experience with the PAL type of bearing indicator leads to a definite recommendation that some form of phase-operated indicator be included in the equipment. Bearing accuracy is improved by this means and the number of times the sound operator finds it necessary to sweep through the target to get a bearing is materially reduced. With a hydrophone each half of which is 3 wavelengths long, targets of equal intensity 15 degrees or more apart may be separated with less than 0.3-degree error, using a frequency band 1 octave wide.

Performance

Bearing Accuracy. Tests at sea indicate that with a line hydrophone 3 wavelengths long, 65 per cent of the bearings are within ±1 degree of the true bearing and 88 per cent within ±2 degrees. These are overall errors, including those due to the equipment, the observers, and the reference which was a visual bearing obtained by means of a range finder. It is felt that errors due to the equip-

ment alone were much smaller and with automatic training under the control of the phase indicator could be reduced to less than ± 0.5 degree.

Estimated Ranges. With the equipment recommended, some estimates of maximum listening ranges are of interest. The signal is assumed to be the sound from a submarine proceeding at 4 knots, periscope depth. The water is assumed to be free of velocity gradients, shallow (less than 100 fathoms) over a hard bottom. The listening boat is drifting in a No. 1 sea and the observer's recognition differential is 6 db. Under these conditions, the estimated maximum listening range is 6,000 yards for sonic frequencies and 5,000 yards for supersonic. For the same conditions but with the boat underway at 6 knots, the estimated ranges are reduced to 1,500 yards and 2,500 yards respectively.

Chapter 6

BEARING INDICATOR SYSTEMS

TWO CLASSES of indicators were developed in order to assist determining bearings with listening gear. The first indicates a null on bearing and gives deflections to right or left when slightly off bearing in the corresponding directions; the second class gives a maximum indication when on bearing.

The first class includes the various types of phase-operated left and right indicator systems, two of which are described below. It also includes the cathode-ray phase indicator. When used with these devices the hydrophone array must be divided into two electrically symmetrical halves having separate electric outputs. The relative phase of the outputs is then compared and the amount by which one leads or lags behind the other is indicated.

Examples of the second class are the volume level indicator, continuous search indicator, and the electron ray level indicator described in this chapter. These devices aid the ear in determining the bearing where the signal is loudest.

Two meter-actuating circuits exemplifying the characteristics of phase operated left and right indicator systems are discussed: the *phase-actuated locator* [PAL] and the *vector bearing indicator* [VBI].[a] One other system of this kind was tested on the *Elcobel* and is described as the cathode-ray phase indicator. However, this latter system was found to be inherently more expensive and more difficult to maintain. Further, the indication presented on the face of the cathode ray tube was too faithful a copy of the unwanted noise peaks which confused the left and right indication. It was therefore discarded in favor of the meter circuits of the type discussed here, which have a considerable advantage in simplicity and cost.

The PAL and VBI circuits represent two versions of the fundamental principle of converting phase differences into level differences. Their operation depends upon the properties of the hydrophone used. Some hydrophone directivity equations will be developed before taking up the indicator systems.

[a] The VBI circuit described here is essentially identical with the *right-left indicator* [RLI] circuit employed by the New London Laboratory and described in Chapter 10.

6.1 HYDROPHONE RESPONSE FORMULAS

General Equation

It is assumed throughout the discussion that the hydrophone has two identical halves, both of which are controlled as to resonances within the passed band and each of which has similar directive properties. They are also assumed to be mounted in the same plane, symmetrically with respect to the center line of the combination. The most general case is one in which the sensitivity varies along the face of each hydrophone as a function of x, the distance from the center line along the horizontal axis. The output of *either* hydrophone at a given frequency for any angle of incidence θ of a sound wave of unit amplitude is given by

$$E = \int_{\pm x_1}^{\pm x_2} f(x) e^{j(\omega t + \alpha)} \, dx, \tag{1}$$

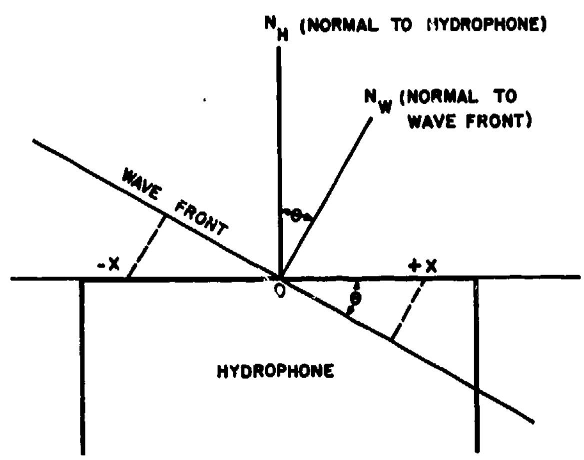


FIGURE 1. Diagram of wave front passing hydrophone.

where $f(x)$ is the law of variation of sensitivity and α is the phase delay of the wave, along the x axis. Referring to Figure 1 which shows the

hydrophone with the normal N_H to its face and the wave front with its normal N_W, the distance the wave has traveled past $+x$ at the time it is passing through zero is

$$x \sin \theta,$$

and the time required to do so was

$$\frac{x \sin \theta}{c},$$

where c is the velocity of sound in the medium. The phase angle may therefore be written

$$\alpha = \frac{\omega x \sin \theta}{c} = \frac{2\pi x}{\lambda} \sin \theta,$$

where λ is the wavelength. Dividing by the integral of the sensitivity function will refer the output at any angle θ to the output at $\theta = 0$, thus

$$E = \frac{\int_{\pm x_1}^{\pm x_2} f(x) e^{j(\omega t + \frac{2\pi x}{\lambda} \sin \theta)} dx}{e^{j\omega t} \int_{\pm x_1}^{\pm x_2} f(x) dx} \tag{2}$$

Special Cases

A special case is shown by Figure 2. Two hydrophones of length L are used, each of which has a symmetrical taper about its center.

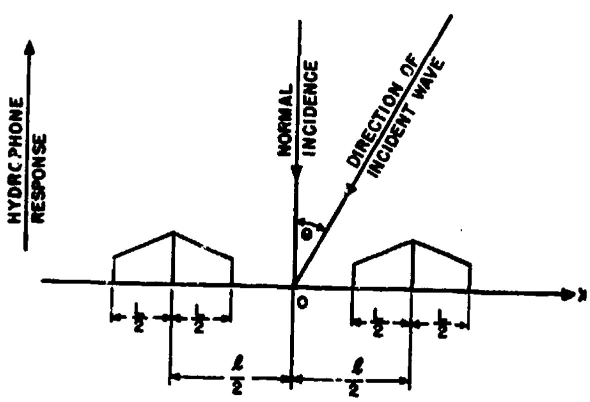


Figure 2. Pair of symmetrically tapered hydrophones.

The output of either one of the pair can be reduced to the product of its directivity function $F(L/\lambda, \theta)$ about its own center and the phase delay of its center with respect to the midpoint of the pair, thus

$$E = Fe^{\pm \frac{j\pi l}{\lambda} \sin \theta} \tag{3}$$

This can be done because the acoustic center of a *symmetrically* tapered line is always coincident with its physical center.

An even simpler case is when the taper is zero and each hydrophone is a uniform line of length l with the two joined together so that their respective centers are at $\pm l/2$. The directivity function F for each half of such a hydrophone is deducible from formulas given in standard texts.

$$F = \frac{\sin\left(\frac{\pi l}{\lambda} \sin \theta\right)}{\frac{\pi l}{\lambda} \sin \theta}. \tag{4}$$

The response then takes the simple form

$$E = \frac{\sin\left(\frac{\pi l}{\lambda} \sin \theta\right)}{\frac{\pi l}{\lambda} \sin \theta} e^{\pm j \frac{\pi l}{\lambda} \sin \theta} e^{j\omega t}.$$

6.2 NULL INDICATORS

PAL Indication

The phase-operated left and right indicator system used with the electrically steered sonic and supersonic arrays and with the mechanically steered 9AA and 6C hydrophones described in Chapter 2 is a development of the PAL system for harbor protection. A block schematic showing the essential elements of the circuit is given in Figure 3. The output of each hydrophone is fed through two independent amplifiers which, in practice, have *automatic volume control* [AVC] to maintain constant levels at their outputs. Identical filters are used to limit the frequency band, and phase shifting networks produce a 90-degree shift in one channel relative to the other before the sum and difference are obtained in the mixing circuit. The sum and difference are rectified and the d-c output of each detector is fed in opposition into a center zero meter. The effects of AVC will be omitted temporarily in the following discussion.

Symmetrically Tapered Hydrophones. Examining each channel separately and including the 90-degree phase shift between channels, we get from (3) for two symmetrically tapered directional lines,

$$\text{Left channel} \quad E_L = Fe^{j(\omega t - \frac{\pi l}{\lambda}\sin\theta)}$$

$$\text{Right channel} \quad E_R = Fe^{j(\omega t + \frac{\pi l}{\lambda}\sin\theta + \frac{\pi}{2})}. \qquad (5)$$

It is now assumed that the detectors are of the square law type. While this is not always the case in practice, the results agree closely with more elaborate computations on linear detectors and with experiments using a band of thermal noise. The rectification process, therefore, squares the real part of the sum and difference expressions above, and the meter response is the result of opposing the d-c portions of the detector outputs, i.e.:

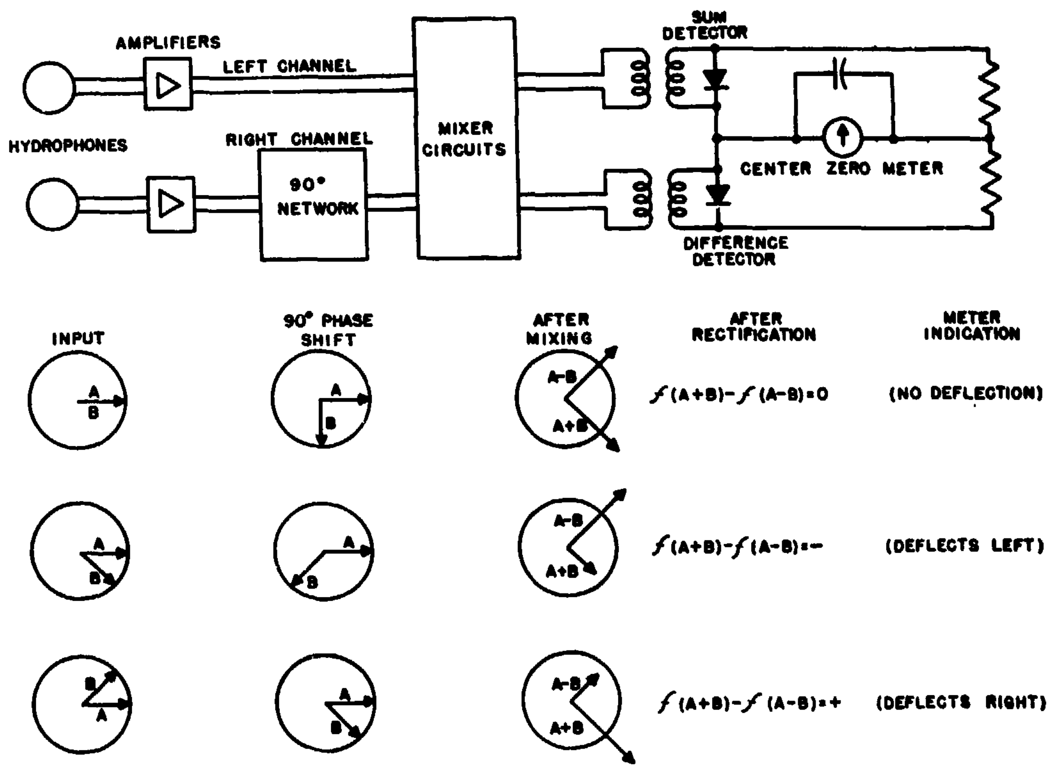


FIGURE 3. Block diagram of PAL circuit.

The sum of these two channels is now obtained in the mixer circuit.

$$S = F\left[e^{-j(\frac{\pi l}{\lambda}\sin\theta)} + e^{j(\frac{\pi l}{\lambda}\sin\theta + \frac{\pi}{2})}\right]e^{j\omega t}$$

$$= F\left[(\cos\alpha - \sin\alpha) + j(\cos\alpha - \sin\alpha)\right]e^{j\omega t}. \qquad (6)$$

Similarly, the difference

$$D = F\left[(\cos\alpha + \sin\alpha) - j(\cos\alpha + \sin\alpha)\right]e^{j\omega t} \qquad (7)$$

where $\alpha = \dfrac{\pi l \sin\theta}{\lambda}$.

$$(\text{Re}\, S)^2 = F^2\left[(\cos\omega t - \sin\omega t)(\cos\alpha - \sin\alpha)\right], \qquad (8)$$

of which the d-c portion is:

$$(\text{Re}\, S)^2_{\text{dc}} = F^2(\cos\alpha - \sin\alpha)^2, \qquad (9)$$

and similarly for the difference,

$$(\text{Re}\, D)^2_{\text{dc}} = F^2(\cos\alpha + \sin\alpha)^2.$$

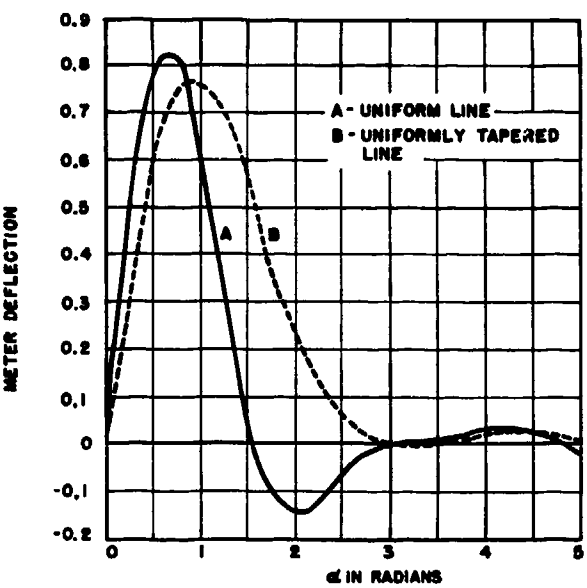
Hence the meter current is:

$$I = (\text{Re}\, S)^2_{\text{dc}} - (\text{Re}\, D)^2_{\text{dc}} = -2F^2\sin 2\alpha. \qquad (10)$$

Uniform Line Hydrophones. For two contiguous uniform lines, equation (10) becomes

$$I = -2\left[\frac{\sin\left(\frac{\pi l}{\lambda}\sin\theta\right)}{\frac{\pi l}{\lambda}\sin\theta}\right]^2 \sin\left(\frac{2\pi l}{\lambda}\sin\theta\right). \quad (11)$$

The results of the computation for the uniform lines are given in Figure 4, curve *A*. The ordinate is the current through the meter and the abscissa is given in terms of $\alpha = (\pi l \sin\theta)/\lambda$, which is measured in radians so that the curve



$$\alpha = \frac{\pi l \sin\theta}{\lambda}$$

FIGURE 4. PAL response with directional hydrophones (single-frequency signal).

is applicable to lines of any length l for any angle of incidence θ. It should be stated that the response follows a similar but inverted curve below the axis on the left side of the null point.

Effect of a Band of Frequencies. The discussion so far has been concerned with a signal consisting of a single frequency. The sound from ship propellers consists of a band of frequencies. Assume for the moment that this may be considered a band of noise whose single-frequency components all have the same intensity at the hydrophone. The meter current is given by an integral of the form

$$I_B = \frac{1}{\omega_2 - \omega_1}\int_{\omega_1}^{\omega_2} I\,d\omega, \quad (12)$$

where the factor preceding the integral serves to normalize it. For two uniform lines, after substituting from equation (11), this becomes

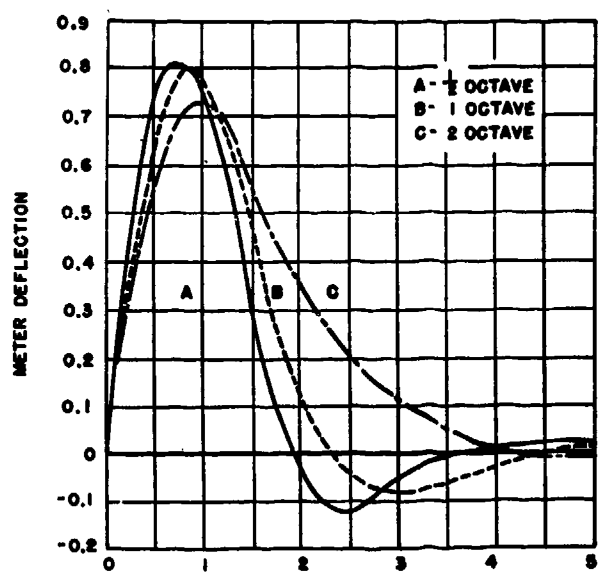
$$I_B = \frac{2}{\omega_2 - \omega_1}\int_{\omega_1}^{\omega_2} \frac{\sin^2\left(\frac{\omega l}{2c}\sin\theta\right)}{\left(\frac{\omega l}{2c}\sin\theta\right)^2}\sin\left(\frac{\omega l}{c}\sin\theta\right)d\omega,$$

$$= \frac{1}{\theta_2 - \theta_1}\Big[\mathrm{Ci}(2\theta_2) - \mathrm{Ci}(2\theta_1) - \mathrm{Ci}(4\theta_2) + \mathrm{Ci}(4\theta_1)\frac{\sin(2\theta_2)}{2\theta_2} + \frac{\sin(2\theta_1)}{2\theta_1} + \frac{\sin(4\theta_2)}{4\theta_2} - \frac{\sin(4\theta_1)}{4\theta_1}\Big], \quad (13)^{b}$$

where

$$\theta_1 = \frac{\omega_1 l}{2c}\sin\theta \quad \text{and} \quad \theta_2 = \frac{\omega_2 l}{2c}\sin\theta,$$

and c = velocity of sound in the medium.



$$\alpha = \frac{\pi l \sin\theta}{\lambda}$$

FIGURE 5. PAL response with uniform line hydrophones (wide-band signal).

The results obtained by keeping the upper frequency fixed while the lower frequency of the band is varied are shown in Figure 5. The curves represent bandwidths of approximately

[b] Ci(α) is the "cosine integral," $\mathrm{Ci}(\alpha) = \int_{\infty}^{\alpha}\frac{\cos u}{u}\,du$, whose values are listed in the standard tables of functions.

½, 1, and 2 octaves. The abscissa is again given in radians and applies to the upper frequency limit. As the band is widened by reducing the lower frequency, the discrimination becomes poorer at most values of the abscissa because of the decreased directionality of the hydrophones at the lower frequencies.

When the hydrophone is trained on the target the meter of the indicator reads zero. The meter may be poled, either to show on which side of the hydrophone axis the target is located (left and right indicator) or on which side of the target the hydrophone is trained. As the hydrophone is trained past the target, the meter may swing through zero a number of times. For instance, for curve A in Figure 5 there is a crossing at $\alpha = 1.9$ radians. This, however, is in the opposite direction to the main crossing at zero and is also very unsymmetrical as regards the right and left excursion of the needle. It can easily be differentiated, therefore, from the true zero. The next crossing is at $\alpha = 3.7$ radians and is in the same direction as the main crossing, but excursions on either side of the zero point are so small that there would be no difficulty in identifying it as a false zero. This becomes increasingly true of crossings at higher angles.

Effect of AVC. It now becomes necessary to consider the effect of AVC on these patterns. There are two reasons for its use. It removes all effects of level changes except those which are proportional to the phase difference in the two channels. The meter deflection then becomes a measure of the number of degrees off bearing. Secondly, it removes the necessity for manual volume adjustment in order to keep the meter deflection within the proper range, not only for the observer's convenience in reading it but to insure that the detector is being loaded to best advantage. The disadvantage of AVC is that it removes the level difference between lobes in the pattern of the hydrophones. The hydrophones, therefore, become essentially nondirective.

Effect of an Interfering Signal. The effect on the meter indication of bringing another sound source into the field can be evaluated by the principle of superposition, that is, by obtaining the pattern for each source separately and adding. A number of patterns, computed for the 9AA hydrophones at different relative levels of target and interference are given in Figure 6 for an angle of 15 degrees between the target and the interference. AVC does not enter this calculation because the two signals go through the amplifiers at the same time and the gain is the same for both. When the two

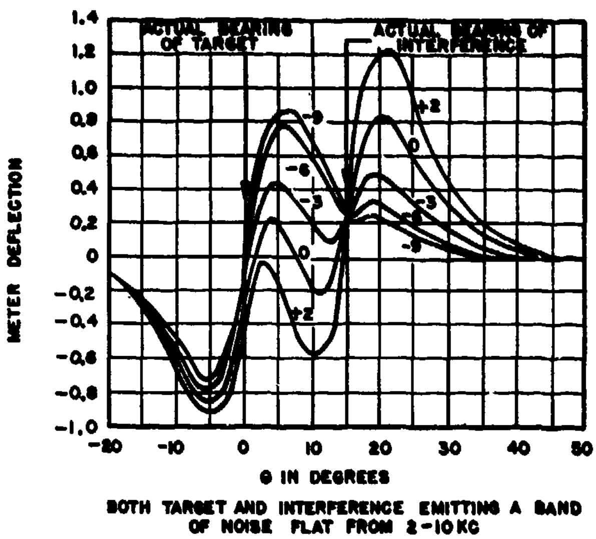


FIGURE 6. Effect of interference in field of target sound.

signals are of equal intensity, they tend to pull their respective zero crossings toward each other by an equal amount which constitutes the error in their respective bearings. When they are 2 db or more apart, the stronger of the two takes over and no bearing can be obtained on the weaker.

Effect of Ambient Noise. The ability of bearing indicators to operate below ambient noise would appear to depend upon the character of the noise. If the distribution is random in angle and the time variation, averaged over a suitable interval, is small, a positive indication is obtained even though the average signal level is below the noise. In such cases the noise level controls the amplifier gain through the AVC which reduces the sensitivity for the signal. Removing the AVC would not improve matters because the noise would then overload the detectors, whose balance cannot be maintained over a very wide range of levels.

Since the meter attempts to follow isolated noise peaks which may be directional, the ob-

served decrease in the standard deviation of ambient noise with increased depth should work to the advantage of this type of indicator on a submarine. Although there have been instances where a bearing could be obtained with the meter beyond the range at which listening alone was effective, there is no positive evidence that its recognition differential is superior to that of the ear.

Effect of Inaccuracy in the Phase-Shift Network. Let us consider the behavior of the circuit over small angles in the vicinity of the null point so that the directivity function F may be omitted. A single frequency is also assumed.

The net gain from hydrophone to mixer circuit is designated by A for the left-hand channel and B for the right. The relative phase shift between the channels is ϕ. The inputs to the mixer circuits are then:

$$\begin{aligned} &\text{Left channel} \quad E_L = Ae^{j(\omega t-\alpha)}, \\ &\text{Right channel} \quad E_R = Be^{j(\omega t+\alpha+\phi)}. \end{aligned} \tag{14}$$

The output of the sum detector is proportional to the real part of the sum squared; expanding and using only the d-c terms, we get

$$(\text{Re } S)^2_{\text{dc}} = \frac{A^2}{2} + \frac{B^2}{2} + AB\,(\cos 2\alpha \cos\phi - \sin 2\alpha \sin\phi). \tag{15}$$

Similarly, the output of the difference detectors is given by

$$(\text{Re } D)^2_{\text{dc}} = \frac{A^2}{2} + \frac{B^2}{2} - AB\,(\cos 2\alpha \cos\phi - \sin 2\alpha \sin\phi). \tag{16}$$

Since these two currents are passed through the meter in opposition, the net meter current is their difference, which is:

$$I = 2AB\,(\cos 2\alpha \cos\phi - \sin 2\alpha \sin\phi). \tag{17}$$

Since A and B are finite, the current becomes zero when

$$\cot\phi = \tan 2\alpha. \tag{18}$$

For this to occur when $\alpha = 0$, ϕ must equal 90 degrees. This is the reason for the fixed 90-degree phase shift.

Any departure from 90 degrees causes the null to shift to a new value of α, say α', and a faulty bearing is obtained. Taking the differential of (18):

$$-\csc^2\phi\, d\phi = \sec^2(2\alpha')\, d(2\alpha'), \tag{19}$$

where α is the angle at which $I = 0$. When ϕ is close to 90 degrees, $\csc^2\phi$ approaches unity. When α is close to 0 degrees $\sec^2\alpha$ approaches unity, hence for small departures from the desired values the variation of α' with ϕ is:

$$d\,(2\alpha') = d\phi = \frac{4\pi l}{\lambda} \cos\theta',\, d\theta', \tag{20}$$

where θ' is the bearing angle at which $I = 0$.

Since α and therefore θ' were assumed to be small,

$$d\phi = \frac{4\pi l}{\lambda}\, d\theta',$$

and

$$\frac{d\theta'}{d\phi} = \frac{\lambda}{4\pi l}. \tag{21}$$

The longer the line in wavelengths, the smaller the bearing error for a given deviation of the fixed phase delay from 90 degrees.

It is apparent from equation (17) that gain variations, including the response of the hydrophones, merely change the magnitude of the meter deflections but do not affect the bearing of the null indication. If the product of the gains, AB, can be maintained constant, there is no change at all in the amount of meter deflection. For this purpose AVC is used, with the result that the meter deflection varies only with the number of degrees off bearing.

Inasmuch as the contributions from various frequency components to the total direct current is proportional to the square of the voltages, the effective phase shift error of the circuit over a band of frequencies can be found from

$$\frac{\int_{\omega_1}^{\omega_2} e^2(\omega)\cdot\Delta\phi(\omega)\cdot d\omega}{\int_{\omega_1}^{\omega_2} e^2(\omega)\cdot d\omega}, \tag{22}$$

which should cover a frequency range somewhat above and below the pass bands of the filters.

VBI Indication

There are a number of different circuit arrangements which can be used to produce a d-c indication of bearing depending on the phase relations of the output of the two hydrophones.

The VBI circuit is shown in Figure 7. The first operation is mixing to obtain the sum and difference. Then the 90-degree phase shift is introduced, after which the two channels are combined in the detector which is essentially another mixer plus a rectifier. Those characteristics of VBI which depend on the directivity of the hydrophones do not differ appreciably from those of PAL which have already been discussed. A principal advantage of VBI is a decreased sensitivity to inaccuracy in the phase shifts within the circuits.

Effect of Inaccuracy in the Phase-Shift Network. For the VBI circuit, the voltage outputs of the two hydrophones are again written in complex form:

$$\begin{aligned} &\text{Left hydrophone} \quad E_L = Ae^{j(\omega t-\alpha)}, \\ &\text{Right hydrophone} \quad E_R = Be^{j(\omega t+\alpha)} \end{aligned} \tag{23}$$

The voltages are then fed into a mixer circuit which forms the sum and difference; these pass through amplifiers with gains C and D, and a phase shift ϕ is introduced into the difference channel thus

$$\begin{aligned} S &= C(Ae^{-j\alpha} + Be^{j\alpha})e^{j\omega t}, \\ D &= D(Ae^{-j\alpha} - Be^{j\alpha})e^{j(\omega t+\phi)}. \end{aligned} \tag{24}$$

The real parts of these sum and difference voltages are combined in a multiplying detector and the d-c output is passed through a center

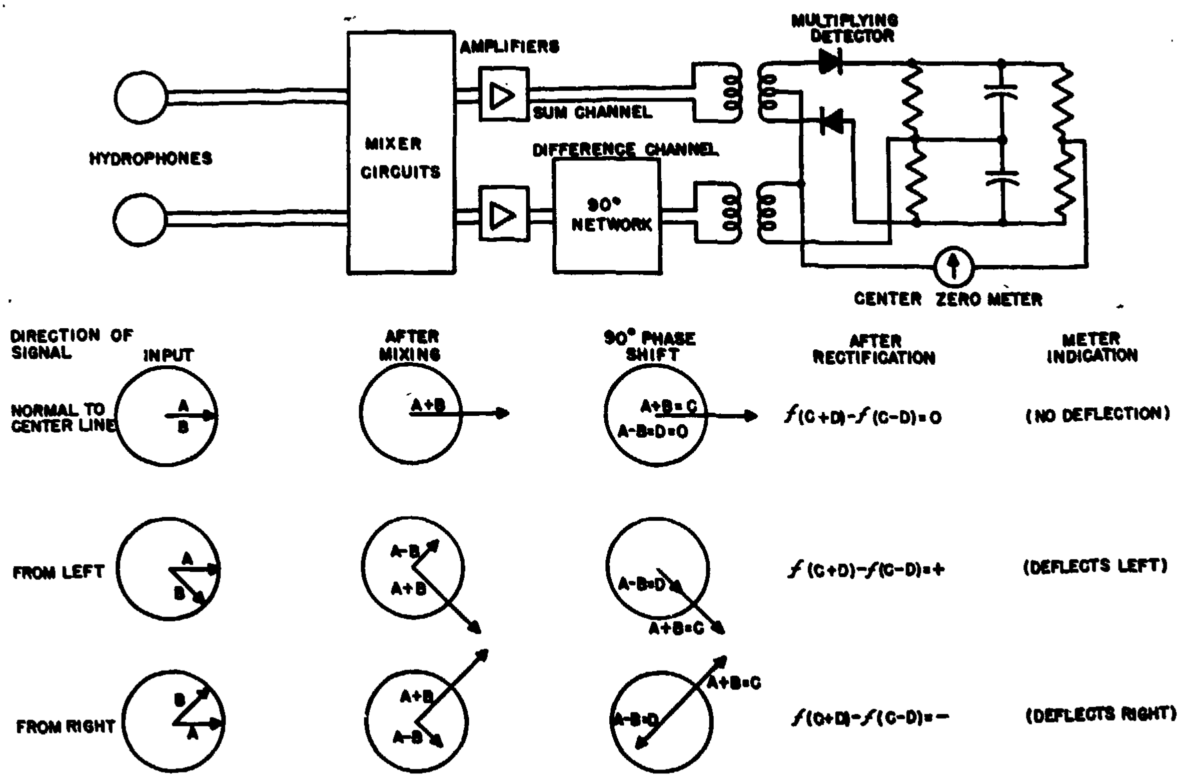


FIGURE 7. Block diagram of VBI circuit.

zero meter. The multiplying detector is really another mixer with square law detectors whose outputs are in opposition. It gets its name from the fact that

$$\begin{aligned} \mathrm{Re}\,(S+D)^2 - \mathrm{Re}\,(S-D)^2 &= 4\,\mathrm{Re}\,(S)\,\mathrm{Re}\,(D) \\ = CD\,[(A+B)^2 &\sin\alpha\cos\alpha\cos\omega t\sin(\omega t+\phi) \\ +(A-B)^2 &\sin\alpha\cos\alpha\sin\omega t\cos(\omega t+\phi) \\ +(A^2-B^2) &\cos^2\alpha\cos\omega t\cos(\omega t+\phi) \\ +(A^2-B^2) &\sin^2\alpha\cos\omega t\sin(\omega t+\phi)]. \end{aligned}$$

After expanding and dropping the a-c terms, the expression for the meter current is

$$I = CD\left[AB\sin 2\alpha\sin\phi + \frac{A^2-B^2}{2}\cos\phi\right]. \tag{25}$$

This discloses the following characteristics of the VBI circuit:

1. The bearing at which a null is obtained is not affected by level differences in the two channels; only the magnitude of the deflection on each side of the null is changed. This is the same as for the PAL circuit.

2. When the two hydrophones feed equal voltages to the mixer circuit ($A = B$), changes in ϕ do not affect the bearing at which a null is obtained. This differs from the PAL circuit [equation (18)].

Near $\phi = 90°$, $\csc^2 \phi$ approaches unity. Near $\alpha' = 0°$, $\cos^2 2\alpha'$ approaches unity. Hence for small departures from these values:

$$\frac{A^2 - B^2}{2AB}\, d\phi = d(2\alpha') = \frac{4\pi l}{\lambda} \cos(\theta') d(\theta') .$$

Since θ is also small when α' is near zero.

$$\frac{d\theta'}{d\phi} = \frac{\lambda}{4\pi l}\left(\frac{A^2 - B^2}{2AB}\right) . \tag{28}$$

The term in parenthesis represents a factor which, for small differences in hydrophone re-

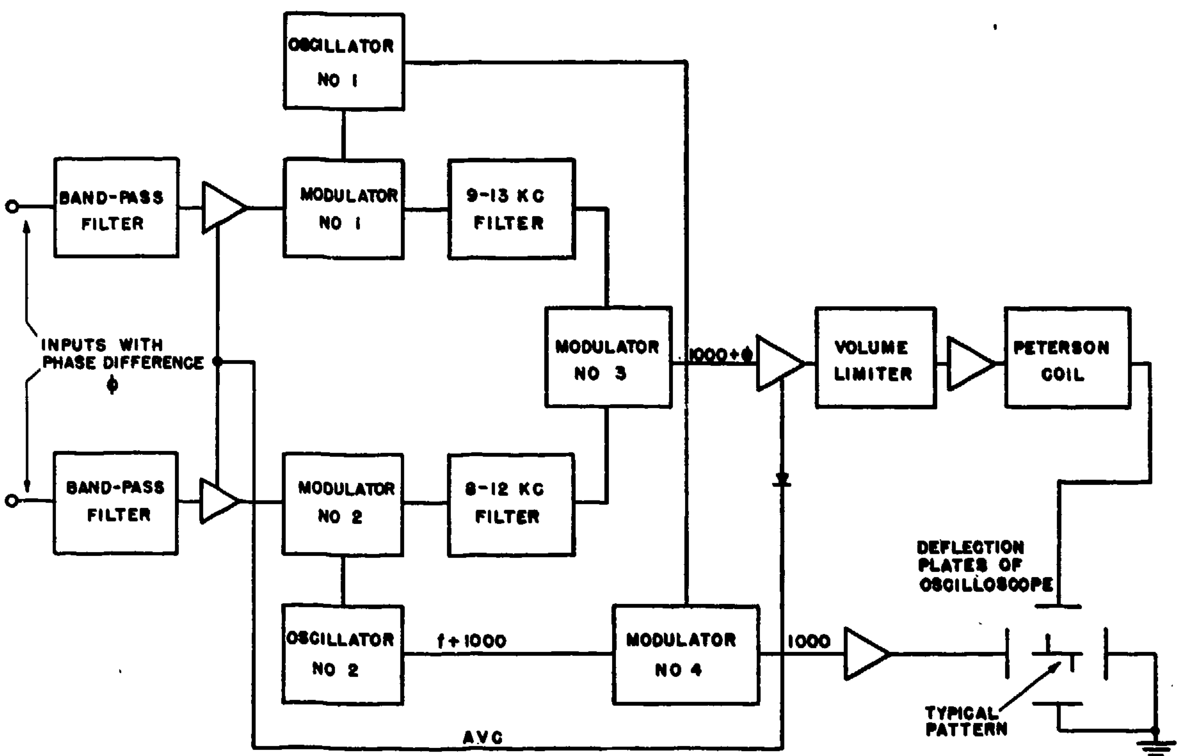


FIGURE 8. Block diagram of cathode-ray phase indicator.

3. When A differs from B and ϕ differs from 90 degrees the null is shifted by an amount which can be determined by equating the current to zero, giving:

$$\sin 2\alpha' = -\cot\phi\, \frac{A^2 - B^2}{2AB} . \tag{26}$$

Differentiating this, leaving A and B constant,

$$\cos^2 2\alpha' d(2\alpha') = \csc^2 \phi\, \frac{A^2 - B^2}{2AB}\, d\phi . \tag{27}$$

sponse, makes the VBI circuit less sensitive than the PAL circuit to phase-shift errors in the amplifiers, networks, and filters of the sum and difference channels.

Cathode-Ray Phase Indicator

An oscilloscopic method of bearing determination, which has been used for other applications, was also tried with the steerable arrays. The pattern obtained on the oscilloscope con-

sists of a horizontal line which has two movable vertical lines extending from it, one below and the other above. When on the correct bearing, the two vertical lines form a single line in the middle of the pattern. When off bearing these lines move apart in a direction which depends factory performance obtained with the PAL. Figure 8 illustrates the principle of the cathode-ray phase indicator. The outputs of the two halves of the hydrophone array are first passed through band-pass filters and amplifiers having AVC. The amplifiers feed into modula-

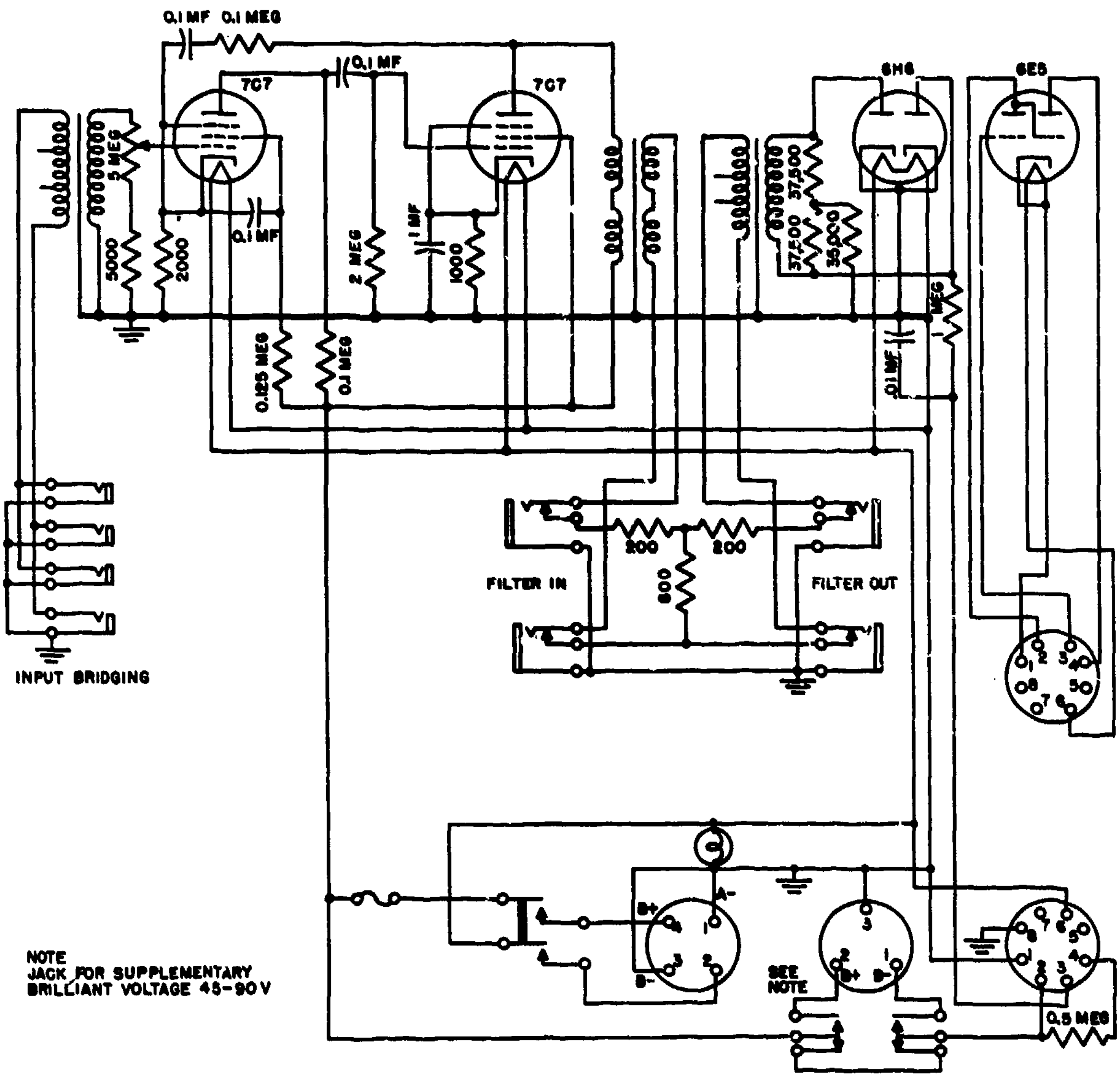


FIGURE 9. Circuit diagram of electron ray level indicator.

upon the direction of the error. Satisfactory performance was obtained with single-frequency inputs but for a band of noise several kilocycles in width the pattern moved rapidly in an irregular fashion so that it was difficult to follow. At this point further work on the equipment was abandoned in view of the satis- tors which are supplied from two oscillators whose frequencies differ by 1 kc. The modulator outputs then pass through an 8- to 12-kc filter on the lower side and a 9- to 13-kc filter on the upper channel which isolate the lower sidebands from the other modulation products. After this they are fed into a third modulator

which yields a difference frequency of 1 kc. The oscillators' outputs are also passed into a fourth modulator which yields another difference frequency of 1 kc. However, these two 1-kc outputs differ in phase by the amount existing at the input terminals. The output of modulator 4

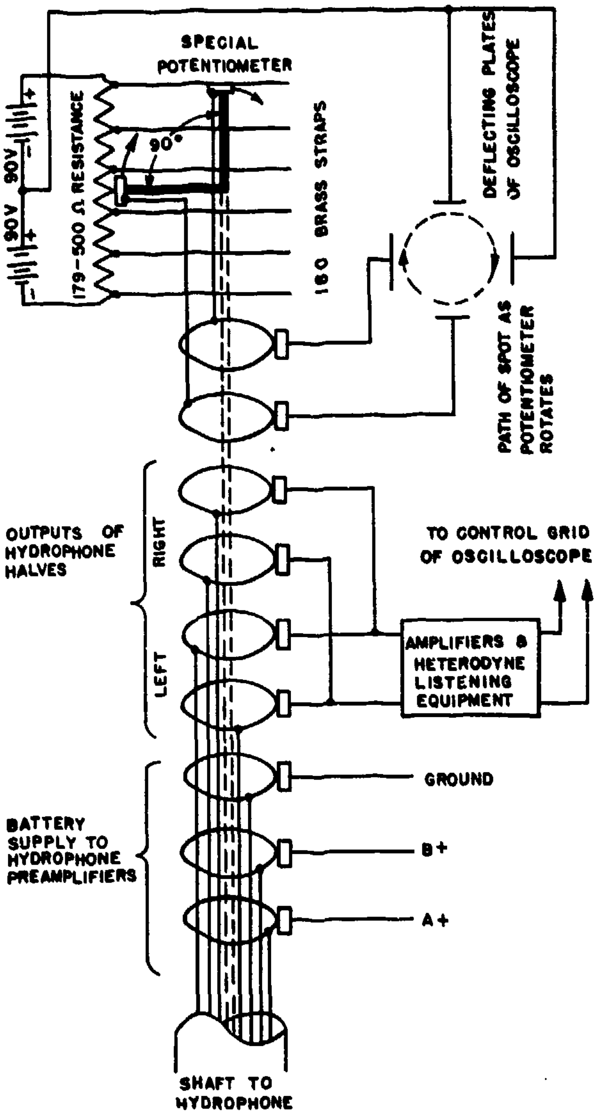


FIGURE 10. Arrangement for indicating bearing while the hydrophone rotates.

is applied to the horizontal plates of an oscilloscope, thus providing a sinusoidal sweep.

The output of modulator 3 could also be applied to the vertical plates directly and thus produce the well-known Lissajous figures which would vary from a straight line having an angle of 45 degrees for zero phase shift to a circle for a 90-degree phase shift. However, a better indication is obtained in the present device by passing the 1-kc difference frequency obtained from modulator 3 through a limiter, which supplements the AVC, and then through a power amplifier to a Peterson coil having an easily saturated core. At the beginning of each half-cycle this coil is not saturated and a voltage is impressed across the vertical plates of the oscillator for a short time. This occurs at the moment that the horizontal plate is in the middle of the line when there is no phase shift, but at an earlier or later time if the phase is leading or lagging. After this brief interval in which the coil is not saturated, the increasing current causes the inductance to drop very close to zero, so that no further voltage appears across the oscilloscope plates until the current again nears zero at the end of the cycle.

6.3 MAXIMUM INDICATORS

Electron Ray Level Indicator

This device is a maximum indicator designed to replace the volume level indicator with a magic-eye cathode-ray tube. It has the advantage of wide ranges in adjustment for the rates of closing and opening the eye. The circuit arrangement shown in Figure 9 consists of a two-stage feedback amplifier followed by a full wave indicator which supplies direct current to the grid of the magic-eye tube. The input of the amplifier is of high impedance so that it can be bridged across a 600-ohm circuit. Between the amplifier output and the full wave indicator, there are transformers to permit the insertion of 600-ohm filters. The overall response is flat within ±2 db from 100 c to 20 kc. A full closure of the eye is obtained on 40 db below 1 volt. The time constant provided is approximately 1/5 second.

Continuous Search Indicator

Continuous rotation of the 6C hydrophone on the *Elcobel* was made possible by means of slip rings attached to the upper end of the shaft.

As shown in Figure 10, an arrangement is provided for indicating on a persistent screen oscilloscope the bearing of a sound source while

the hydrophone rotates. The output of the two halves of the hydrophone are connected in parallel, amplified and heterodyned down to the audio range, and then fed to the *Z* amplifier of this oscilloscope which controls the intensity of the spot. The position of the spot is determined by a special potentiometer. The brushes are attached to arms at right angles to each other and connected to the deflecting plates of the oscilloscope through two slip rings.

As the hydrophone is rotated by a belt drive from a motor and gear reduction box, the voltage applied to the deflection plates varies sinusoidally, the horizontal plates being 90 degrees out of phase with the vertical plates so that the spot is moved in a circular path. Since the intensity of the spot is controlled by the hydrophone output, a bright section of the circumference can be seen on the screen when the hydrophone passes through the bearing of a sound source. Random noise appears as scattered dots. Although the locations of sound sources are shown on the oscilloscope screen, the traces are rather broad, since they follow the beam width of the transducer and isolated noise peaks contribute meaningless bright spots. It was found that some means were needed for sharpening the indication as well as a method for discriminating against random noise peaks.

Chapter 7

SURFACE CRAFT LISTENING EQUIPMENT— JP SYSTEMS

7.1 INTRODUCTION

THE SMALL CRAFT engaged in coastal patrol work consisted mostly of converted private yachts and fishing vessels about 50 feet to 100 feet in length. Because of their small size and inadequate armament, it was the primary function of these vessels to report the location of enemy submarines rather than to attack them. Echo ranging was not feasible from ships of this size, particularly with the type of equipment in existence at that time, nor was sufficient gear available to equip the small craft for this function. Sonic listening appeared to be practicable for patrol craft search of submerged submarines and submarines at night.

It was believed that to be useful in detecting submarines from small patrol craft such sonic equipment should have a listening range of several thousand yards under good conditions and should be capable of indicating the target bearing to within a few degrees. The mechanical part of the gear should be easily adjustable to accommodate installation on widely varying types and sizes of vessels, and its operation should not contribute appreciably to the background noise level.

On this basis, two types of directive sonic detectors were developed, an overside equipment and, later, a through-the-hull equipment. To simplify production and to avoid the necessity for drydocking the vessels during installation, an overside type of gear was chosen for primary development in spite of the mechanical and hydrodynamical advantages of a through-the-hull design.

Design Principles

The requirements demanded a hydrophone having sufficient efficiency to insure an adequate signal to resistance-noise ratio in the sonic region[a] and sufficient size to provide reasonably sharp directivity in the upper sonic frequencies. To avoid ambiguity between reciprocal bearings, the hydrophone selected had a front-to-back discrimination of at least 10 db over a broad frequency range.

The amplifier was designed to have a uniform frequency response from about 0.1 kc to 10 kc. Several supplementary high-pass filters were provided to permit progressive exclusion of the lower frequencies, when desired, in order to discriminate against certain types of background noise and to take advantage of greater hydrophone directivity at the higher frequencies. To supplement loudspeaker and headphones, an indicator such as a magic-eye tube was found desirable in aiding determination of bearings.

The mounting and training gear were designed to locate the hydrophone an appreciable distance below the keel to avoid acoustic shielding by the hull and to provide for easy and accurately controlled rotation of the hydrophone from a training wheel which was located in the deckhouse.

Uses of Experimental Gear

Fifty preproduction units of the overside gear were installed for tests and training purposes. A total of 1,500 units was produced, but they were not placed in service because of the removal of enemy submarine activity from coastal waters. However, the design principles and experience gained were utilized in the development of topside directive sonic listening gear used on U. S. submarines and discussed in Chapter 10 of this volume.

[a] For a 1 cycle wide band, minimum measurable pressure not greater than –34 db vs 1 dyne per sq cm at 0.1 kc, –54 db at 1 kc, and –74 db at 10 kc.

FIGURE 1. Hydrophone and baffle for JP overside equipment.

JP Overside Equipment

The JP overside equipment is designed to be used on small patrol craft to pick up the underwater sounds of submarines and indicate their direction from the ship. The equipment consists of a directional toroidal magnetostriction hydrophone, a sonic amplifier with battery power supply, and a training mechanism. The hydrophone is mounted on a shaft extending into the water over the side of the vessel. Because of the method of suspension, the system can be used to advantage only in relatively calm seas. The listening vessel must be lying to with all machinery secured. The hydrophone response rises with frequency at the rate of about 3 db per octave from a value of −115 db vs 1 volt per dyne per square cm at 1,000 c. The amplifier has a flat frequency characteristic in the range 0.2 kc to 10 kc and is equipped with a series of four high-pass filters cutting off at 500 c, 1,500 c, 3,000 c, and 5,500 c. This equipment was developed by CUDWR-NLL.

7.2 PRELIMINARY WORK

A bidirectional toroidal magnetostriction hydrophone[b] developed earlier was selected as the type of available unit most readily adaptable to the requirements of the directional sonic listening equipment. Various types of acoustic baffles, including foam rubber, waterproofed cellular fiberboards, a heavy slab of litharge-impregnated rubber, and an iron ring with cork-rubber backing were tried as means of making this hydrophone unidirectional to permit unique bearing determinations. Of these, the last two met both the structural and acoustic requirements, and the iron ring with cork-rubber backing was selected because less rubber was required.

An ordinary rubber hose-type coupling, tried as a means of providing the necessary flexibility to allow the overside hydrophone support to hang vertically in the water, was rejected when tests showed it to be inadequate during heavy rolling and pitching. A gimbal type of joint proved superior to the hose but still permitted the hydrophone shaft to depart considerably from the vertical in the presence of strong winds and tides. As no simple means of eliminating this deficiency in the overside gear was apparent, the gimbal type of coupling was adopted because of lack of further development time.

[b] Magnetostriction hydrophone developments are discussed in Division 6, Volume 13.

7.3 FINAL OVERSIDE EQUIPMENT[1,2]

HYDROPHONE AND BAFFLE

The overside listening equipment hydrophone is a magnetostriction unit using 2-inch outside diameter nickel tubing curved to the shape of a toroid 24 inches in diameter. It is normally bidirectional, with major response lobes along the axis of the toroid, and has a sensitivity which increases with frequency at the rate of about 3 db per octave from a value of −115 db vs 1 volt per dyne per sq cm at 1,000 c. The acoustic baffle consists of a ¼-inch thick flat iron ring 3 inches wide backed with a ½-inch layer of cork-impregnated rubber. This provides a front-to-back discrimination of 10 db to 15 db at frequencies of 1 kc and higher. The baffle is mounted on the training shaft and the hydrophone is secured to it by means of U-shaped molded rubber clamps which aid in isolating the hydrophone from mechanical

vibration of the shaft. When not in use, the shaft is swung alongside and the whole assembly pulled inboard so that the hydrophone may be stowed on deck.

Hydrophone Shaft and Training Mechanism

The hydrophone shaft, of 2-inch standard pipe, contains concentric rubber-in-shear shock

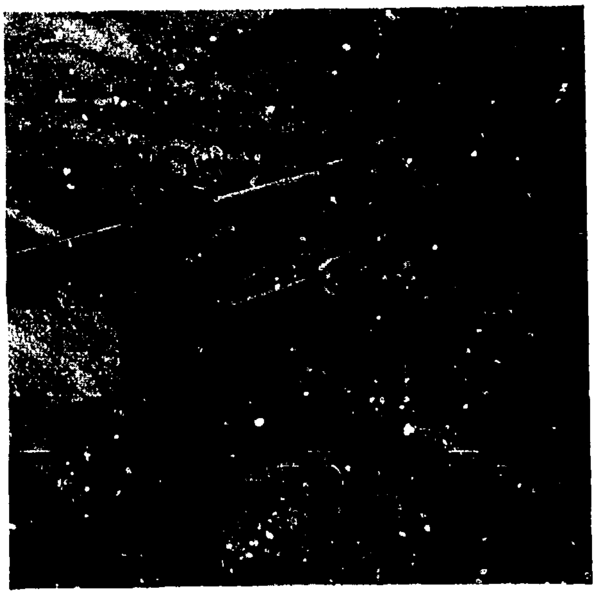


Figure 2. Overside equipment gimbal-type yoke.

mounts at top and bottom to minimize transmission of vibration incident to use of the training mechanism. The top of the shaft is secured to a cast bronze gimbal-type yoke (Figure 2) which allows the shaft freedom to swing in two directions. The gimbal is connected to the inboard mechanism (Figure 3), which includes a training wheel and azimuth indicator, by means of a second length of 2-inch standard pipe. Through this pipe are run ¹⁄₁₆-inch stainless-steel stranded cables to rotate the hydrophone shaft in synchronism with the motion of the training wheel.

Amplifier and Power Supply

The amplifier is of the impedance- and resistance-coupled type employing six tubes. It has a voltage gain of approximately 115 db and a uniform frequency response over the range 0.2 to 10 kc. The circuit includes four high-pass filters cutting off at 500, 1,500, 3,000, and 5,500 c immediately selectable by means of a rotary switch. High-quality headphones are used for listening and an electron-ray indicator tube (magic-eye), associated with the 5,500-c filter position is provided for determining bearings more accurately than by listening alone.

The power supply for the amplifier is independent of the ship's supply. It consists of a 6-volt storage battery for the filaments plus four heavy-duty 45-volt B batteries. A 480-μf bank of condensers, charged by the 180-volt

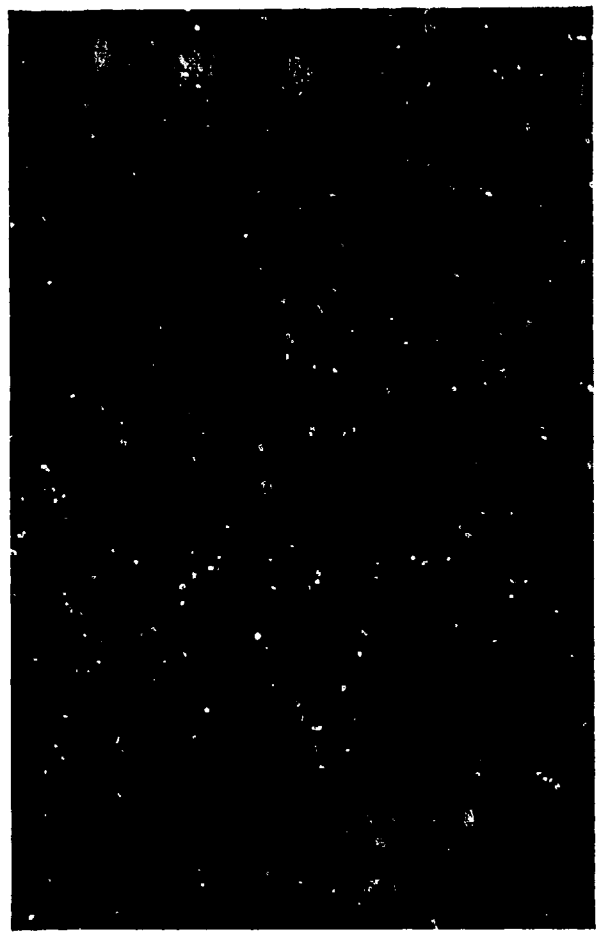


Figure 3. Overside equipment inboard assembly.

plate supply and discharged through the coil of the hydrophone, furnishes a peak current of approximately 13 amperes for remagnetizing the nickel tube.

7.3.1 Performance

In general, the overside equipment performs satisfactorily only in relatively calm seas and with moderate winds. Under good conditions, ranges of 3,000 yards or more and bearing accuracies of $\pm 2\frac{1}{2}$ degrees can be obtained. In rough water or strong winds, however, performance of the overside equipment is seriously impaired, owing primarily to failure of the hydrophone shaft to remain vertical in the water and to the added water noise caused by the violent motions of the hydrophone.

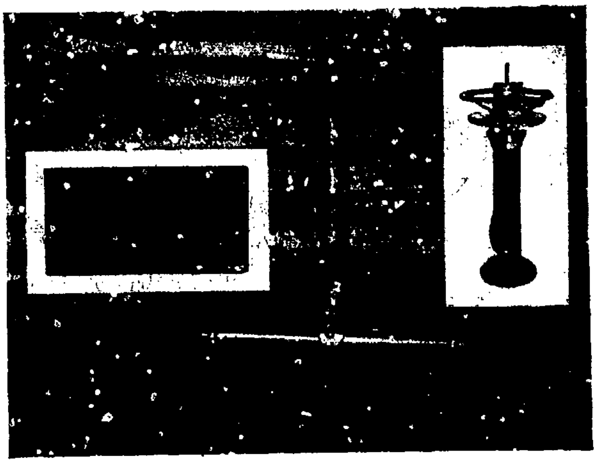


FIGURE 4. JP through-the-hull equipment.

JP Through-the-Hull Equipment

The JP through-the-hull equipment, developed by CUDWR-NLL, is used by small patrol craft to pick up submarine sounds and indicate their relative direction. The equipment consists of a 3-foot toroidally wound magnetostriction line hydrophone with baffle, sonic listening amplifier, battery power supply, and training mechanism. The hydrophone is mounted on a shaft which extends through the hull and can be raised for stowing or lowered for listening. The system can be used while the vessel is under way at 3 or 4 knots under sail, with all machinery secured. The hydrophone with its baffle is directional and its response rises with frequency at the rate of about 6 db per octave from —110 db vs 1 volt per dyne per square cm at 1,000 c. Amplifier and power supply are those used with the JP overside equipment.

After completion of the overside equipment, development was directed toward design of a through-the-hull type of training mechanism to overcome the mechanical shortcomings of the overside gear and provide for continuous underway listening at slow speeds. Because a sea chest to house the hydrophone when the vessel was moving at high speed could not be accommodated by most of the small patrol craft, it was necessary to provide a unit having less drag than the toroidal hydrophone used with the overside gear. For this purpose a 5-foot long, straight magnetostriction hydrophone of wooden core construction[c] was selected. Equipped with a streamline air column baffle, this unit provides minimum drag together with good directivity and front-to-back discrimination.

Calculation showed that, at 8 knots, a $3\frac{1}{2}$-inch diameter shaft is required to withstand the drag of the straight hydrophone and baffle mounted 5 feet below the hull. Later tests indicated, however, that the hydrophone could be mounted as close as 30 inches to 36 inches below the hull without impairing performance.

7.4 FINAL THROUGH-THE-HULL EQUIPMENT

The through-the-hull equipment[2] utilizes the same power supply developed for use with the overside gear. The hydrophone and the mechanical arrangements differ, and the amplifier is modified to operate either on batteries or on the 110-volt d-c ship supply.

HYDROPHONE AND BAFFLE

The hydrophone and baffle assembly used with the final model of the through-the-hull equipment is shown in Figure 5. The hydrophone, a 3-foot long, plastic-covered toroidally wound magnetostriction unit[3] has less susceptibility to magnetic interference from generators, vibrators, dynamotors, etc. than the conventionally wound straight magnetostriction unit. Its sensitivity increases with fre-

[c] Magnetostriction hydrophone developments are discussed in Division 6, Volume 13.

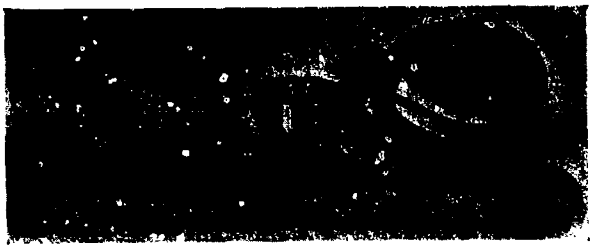


FIGURE 5. Through-the-hull hydrophone and baffle assembly.

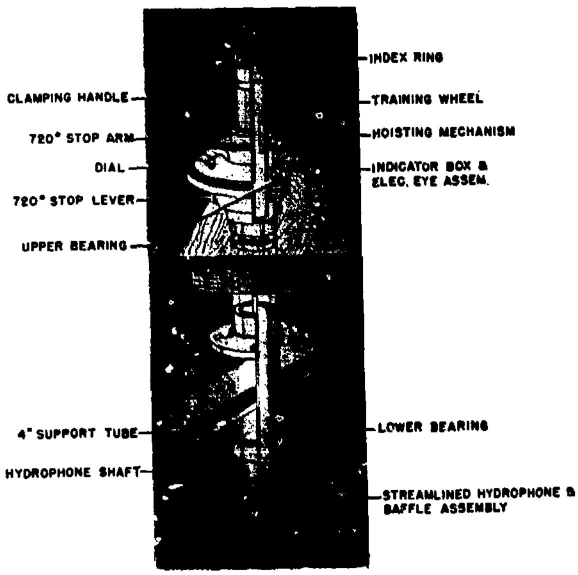


FIGURE 6. Through-the-hull hoist-train assembly.

quency at the rate of about 6 db per octave from a value of −110 db vs 1 volt per dyne per sq cm at 1,000 c. The lowest measurable pressures with this unit for a 1-cycle band at 0.1 kc, 1 kc, and 10 kc are respectively −62 db, −74 db, and −75 db vs 1 dyne per sq cm. The baffle consists of a streamline, free-flooding, hollow bronze casting covered on the backside with a non-intercommunicating cellular rubber blanket. This construction was found to give better front-to-back discrimination than the non-free-flooding air column baffle used formerly.

HOISTING-AND-TRAINING MECHANISM

The through-the-hull mechanical arrangement is shown in the sectional drawing, Figure 6, which illustrates the method of installation. The support tube, or well, consists of 4-inch standard iron pipe and the training shaft is of 3-inch seamless-steel tubing plated with successive layers of copper, nickel, and chromium. The shaft is secured at the top to the training

FIGURE 7. Through-the-hull inboard assembly; shaft in raised position.

handwheel and bearing-dial assembly which rotates in a ball-type bearing. At the bottom the shaft is supported laterally by a graphited

asbestos sleeve bearing which requires no machining of the smoothly plated shaft.

The hoisting mechanism for raising and lowering of the hydrophone consists of a rack gear milled into the training shaft, meshing with a pinion gear which is turned by a demountable hand crank. A safety lock prevents raising of the shaft unless the hydrophone is oriented fore and aft with respect to the ship.

The bearing dial moves with the training shaft so that relative bearings are indicated by a stationary pointer secured to the nonrotating supporting structure. Both the bearing dial and the pointer are illuminated indirectly from below, and a magic-eye indicator is mounted beside the pointer. Mechanical stops prevent rotation of the shaft through an angle of more than 720 degrees to avoid fouling the cable from the hydrophone. The through-the-hull inboard assembly is shown in Figure 7 with the shaft in the raised position.

7.4.1 Performance

The through-the-hull equipment performed satisfactorily even in moderately rough seas. For a large number of trials, bearing accuracies averaged better than ± 2 degrees and ranges of over 6,000 yards were obtained on a moderately noisy submarine running submerged at high speed. Listening was found to be possible without serious interference at ship speeds up to 3 or 4 knots under sail.

7.5 SUGGESTED DESIGN IMPROVEMENTS

It is believed that the performance of the through-the-hull directive sonic listening equipment can be improved in several important respects. (1) The use of a permanent-magnet type of magnetostriction hydrophone would eliminate the need for remagnetizing circuits. (2) A rubber coupling in the shaft would minimize the transmission of vibration from the hull to the hydrophone. (3) A streamline dome over the hydrophone would permit listening at speeds greater than 3 or 4 knots under sail. (4) Continuous rotation of the hydrophone by means of an electric motor drive (with provision for hand training after location of a target) would greatly reduce operator fatigue.

Chapter 8

AIRCRAFT LISTENING EQUIPMENT—TOWED HYDROPHONES

8.1 INTRODUCTION

BEFORE THE ADVENT of aircraft listening equipment, patrol blimps had little means of detecting the presence of submerged submarines. Prior to the radio sono buoy program, as described in the following chapter, the use of towed hydrophones for this purpose was investigated. It was proposed that submarines intercepted on the surface could be tracked after submergence by a hydrophone lowered from the slowly moving aircraft.

The two types of towed listening gear developed for this purpose were a single directional line hydrophone and a pair of nondirectional hydrophones adapted for binaural determination of bearing. Tests of these experimental models indicated that the designs of the hydrophone housings permitted listening at water speeds of 20 to 25 knots. However, under most conditions the drag resistance of the hydrophone cable that was used with both sets of gear restricted the operation to lower speeds. It was concluded that a radical reduction of the cable's drag-tensile strength ratio, accompanied by possible changes in its weight coefficient, would be necessary to produce significant improvement in its towing characteristics. Since the minimum cruising air speed of the Navy K9 blimp is 20 to 25 knots, the hydrophones could not be used in their experimental form. Official interest was transferred from the towed hydrophone program to the more promising radio sono buoys with no further improvements undertaken by the National Defense Research Committee [NDRC].

8.2 DESIGN CONSIDERATIONS

The problems encountered in the development of towed underwater listening gear are divisible into two parts, electric and mechanical. From the electrical standpoint, the design of transducer units with proper sensitivity and directivity characteristics was straight-forward. The mechanical considerations, however, included selection of a streamlined shape for the hydrophone housing that would produce no turbulence at the speeds anticipated. The trim and stability of the housing had to be adjusted so that the hydrophone would follow its cable without yawing. In the case of the paired hydrophones for binaural listening, this stability had to be sufficient to permit accurate determination of the underwater relative position of the hydrophones by adjustment of the two cable lengths from the blimp control point. Above all, the behavior of towed cable required study. Cable drag is so important in towing these bodies that, to a first approximation, it alone seems to determine the towing load. Both the towing depth of the hydrophone and the permissible speeds for listening were restricted by the towing characteristics of the cable.

In studying the behavior of cable, a general curve was derived which gives the shape of a towed cable in air or water for a wide range of speeds and loads. This permits the prediction of the depth of a towed body from physical parameters which can be determined directly. Other measurements, made to determine the depth of a body as a function of the length of submerged cable and the speed, led to an empirical formula which showed the depth for a given length of cable to be inversely proportional to the square of the towing speed. Because of the difficulty of obtaining sufficient towing depths at high speeds with simple streamlined bodies and cables, diving wings and depressors have been used in the design of other towed devices.[a]

[a] As described in the section on the SR-2 practice target, Division 6, Volume 4, Chapter 10.

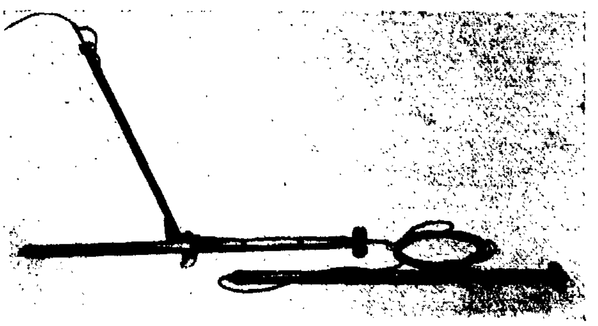


FIGURE 1. Blimp-towed hydrophone with diving tractor.

Blimp-Towed Hydrophone

The blimp-towed hydrophone is an experimental directional magnetostriction line hydrophone developed by CUDWR-NLL to be towed 40 feet behind a streamlined diving tractor that is itself towed by an aerial cable lowered from a patrol blimp. Underwater sounds in the angle of the hydrophone's listening beam can be detected by the operator aboard the blimp. Streamlined housing permits towing without significant turbulence at speeds up to 25 knots. In practice, unsatisfactory towing characteristics of the cable used with this device restrict towing to lower speeds inadequate for general use by patrol blimps.

CONSTRUCTION

The blimp-towed hydrophone, as shown in Figure 1, consists of the hydrophone, cable, and diving tractor. The streamlined housing of the hydrophone, consisting of a 2-inch cylindrical body 4 feet long, with tapered nose and a four-wing stabilizing tail, permits towing at speeds up to 25 knots with no significant turbulence. A weighted nose provides proper trim so that the hydrophone travels behind its tractor with a fairly stable course, although several tests showed a tendency to yaw from side to side.

The tractor serves to separate the hydrophone from the water noise of the feather where the towing cable enters the water. The tractor, shaped like the hydrophone housing, has a 2-inch cylindrical body, 63 inches long, with a four-wing stabilizing tail. A diving vane projects on either side from the center of the tractor body. A 36-inch towing arm projects upward to conduct the towing cable from the sloping aerial direction to a horizontal position. A special cable anchor at the top of the towing arm distributes the load equally among the cable strands to insure towing strength.

Several types of cable were tested with this hydrophone. A tensile strength of 1,500 pounds was found adequate to carry the towing load as well as the additional yawing load. The further provisions of electrostatic shielding and a waterproofing cover were judged necessary for a satisfactory final design. These changes would eliminate the introduction of induced voltages due to radio interference in the long aerial part of the cable and the galvanic interaction of dissimilar metals in sea water.

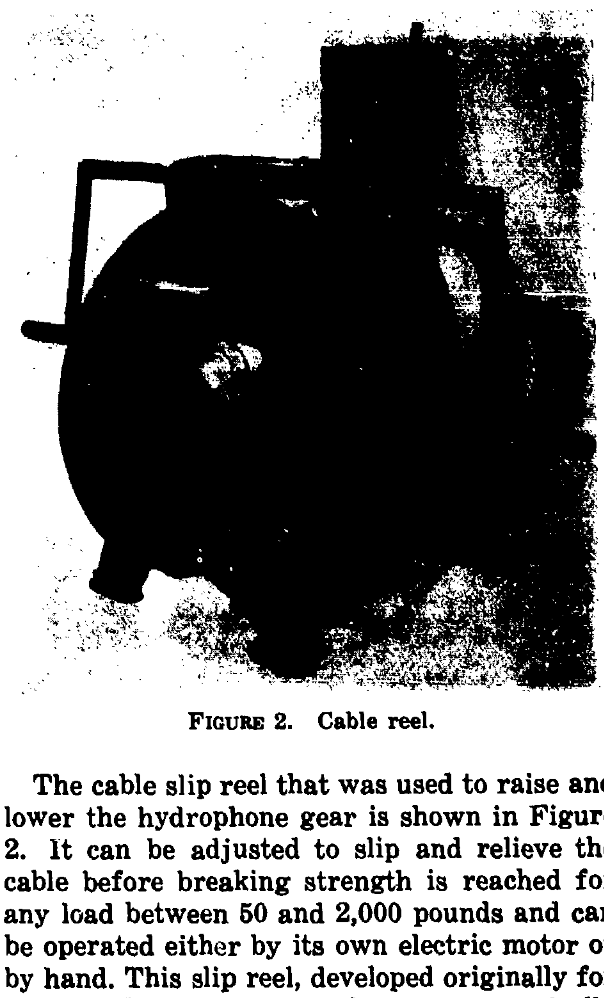


FIGURE 2. Cable reel.

The cable slip reel that was used to raise and lower the hydrophone gear is shown in Figure 2. It can be adjusted to slip and relieve the cable before breaking strength is reached for any load between 50 and 2,000 pounds and can be operated either by its own electric motor or by hand. This slip reel, developed originally for towing gliders from airplanes, automatically compensates for variable strains on the towing structure.

Acoustic Performance

The construction of the magnetostriction line hydrophone provides a directivity pattern with main lobes on either side of the line of tow. The sharp lobe produced by a single winding of a 6-foot hydrophone that was used early in the program proved impractical in tests. The 4-foot hydrophone was wound in three sections to provide somewhat broader lobes and was sufficiently sensitive to demonstrate the feasibility of listening with towed gear of this general design. In evaluation tests made by the Navy at the Lakehurst Naval Air Station in the summer of 1945 a freighter was heard at a distance of 5 miles at towing speeds up to 25 knots. If further development had been carried out, a conventional baffle would have been introduced to eliminate one of the lobes. There was also some preliminary discussion of incorporating a relay control to rotate the direction of the listening beam, since a hydrophone which cannot vary its listening direction relative to its course is of limited value. It was felt, however, that for real search efficiency a more complicated hydrophone circuit would be required.

Towing Performance

Sufficient tests were made of the blimp-towed hydrophone, both from blimps and from surface vessels, to demonstrate the satisfactory design of the housing and the need for radical improvement of the towing cable. Whereas listening was possible at water speeds up to 25 knots when the hydrophone was towed from a blimp, this top speed was reduced to 10 knots in towing from a surface vessel because of the necessarily increased length of cable submerged. Failure of the lightweight cable, under the load of yawing and of cable drag, interrupted several tests. Further study would require change of the cable as a first step in improving the design. Since the K9 blimp cannot travel at cruising air speeds less than 25 knots, the use of the hydrophone is limited to upwind and occasional crosswind courses.

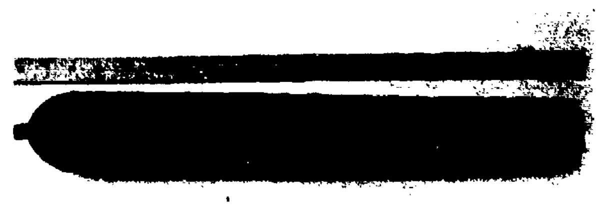


Figure 3. HW-towed hydrophone.

HW-Towed Hydrophone

The HW-towed hydrophone is a nondirectional Rochelle salt hydrophone developed by MIT-USL to be towed in pairs from a patrol blimp to permit binaural detection of underwater sounds. Streamlined housing permits towing without observable turbulence at speeds up to 20 knots. However, unsatisfactory characteristics of the towing cable restricted the towing to lower speeds which were not sufficient for general use by patrol blimps.

Construction

The HW towed hydrophone, shown in Figure 3 and schematically in Figure 4, consists of a nondirectional crystal transducer housed in a streamlined body, attached to a ½-inch cable. The HW body is 21 inches long and 7 inches in diameter, weighing 7.5 pounds in air and 3.3 pounds in water. By weighing the nose of the HW and adjusting the size of the tail fins, the trim and stability were adapted for high-speed towing. Although the development of the radio sono buoys for listening from aircraft led to

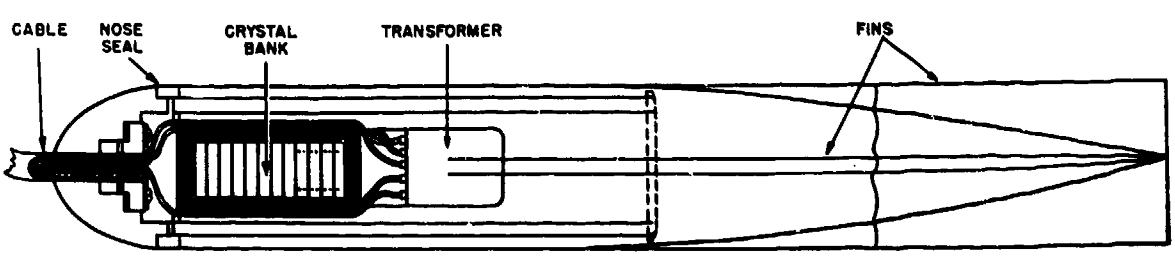


Figure 4. Schematic drawing of HW-towed hydrophone.

withdrawal of official interest from the towed hydrophone development, the HW was used in laboratory measurement programs, towed from surface ships to study ship sounds.

Inside the HW body, a bank of Rochelle salt crystals is housed with a crystal-to-line transformer. The crystals are connected in parallel and held in a rigid frame. The pressure faces of the bank are coupled to the seawater through a film of castor oil and the flexible rubber walls of the body.

Acoustic Performance

The frequency response of the HW hydrophone, shown down to 1 kc in Figure 5, is flat within ± 2 db from 0.15 to 10 kc, measured across a matching load. This permits satisfactory listening at low frequencies. The directional pattern of the HW, shown in Figure 6, is fairly uniform both in the planes containing and the planes perpendicular to the axis. With increasing frequency the sensitivity shrinks opposite the nose and tail of the HW body.

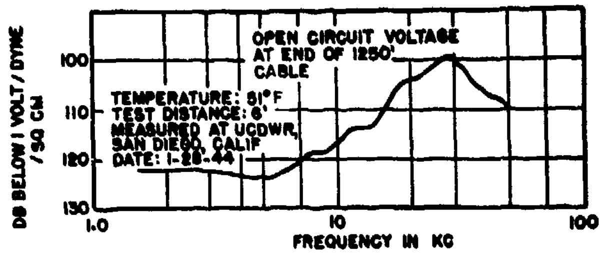


Figure 5. HW frequency response.

In binaural listening the nondirectional feature permitted matching the phase of the separate audio signals in a pair of earphones. The relative positions of the two hydrophones in the water could be adjusted until, by the binaural discrimination of the human ear, matching was recognized. The auxiliary equipment consisted of two identical receiver channels, with equal lengths of cable and identical amplifiers, so that the two signals were equal in level. With this equipment the relative position of a merchant vessel several miles off could be determined. No quantitative measurements were made in the tests of binaural listening.

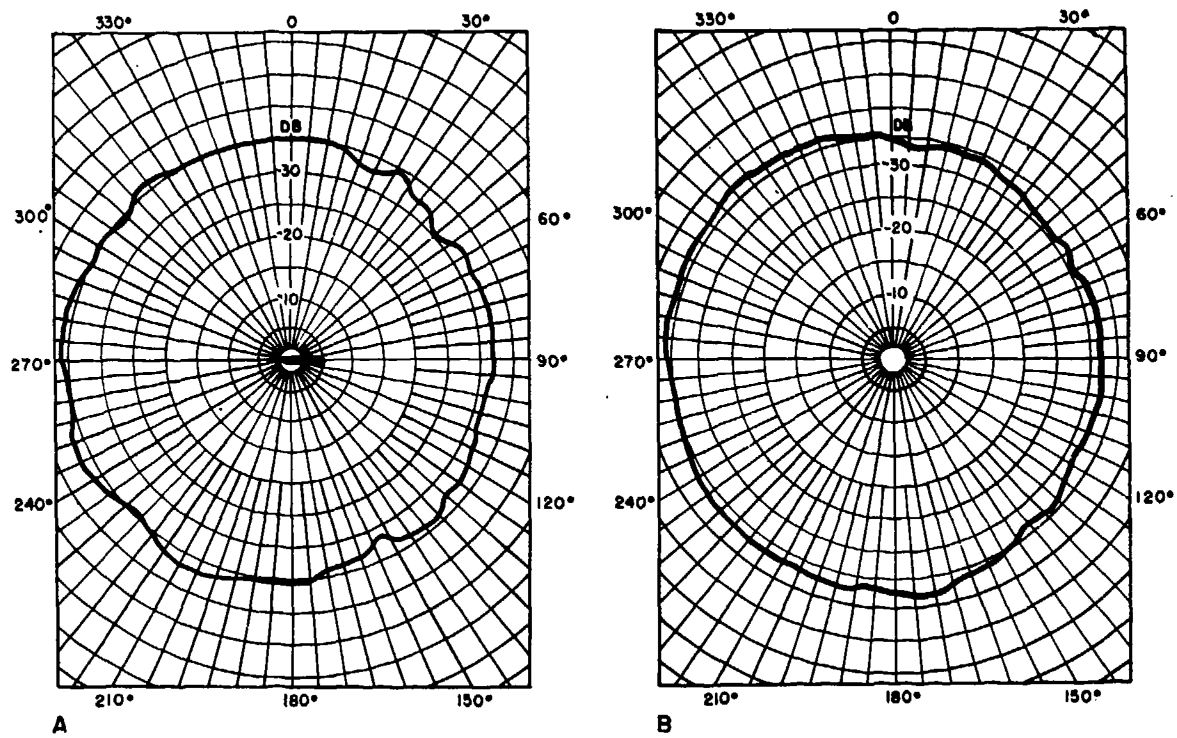


Figure 6. Directivity patterns of HW-towed hydrophones measured at 3 kc; (A) measured in a plane containing the axis; (B) measured in a plane perpendicularly bisecting the axis.

HW Towing Performance

The stability of the HW hydrophone as a towed body was demonstrated in several tests. No turbulence of water along the housing was observed at speeds up to 20 knots. It is interesting to note that the HW reduced the vibrations of the cable, cutting down the total towing load. This was demonstrated in tests of a given length of cable with and without an HW. No yawing was perceptible from the blimp. A pair of HW's towed in parallel from points 6 feet apart maintained this separation in the water, turning together in parallel courses as the blimp changed direction. This stability made it possible for the binaural operator in the blimp to determine the accurate position of the hydrophones by adjustment of the length of cable.

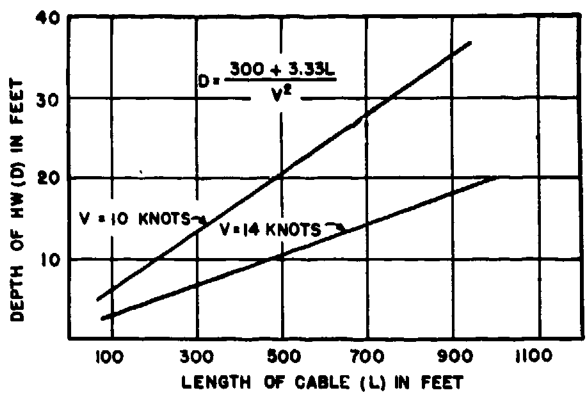


Figure 7. Depth-cable length plot for HW-towed hydrophones.

The depth at which the hydrophone travels depends upon the trim of the HW housing, the towing speed, and such characteristics of the cable as its towing angle, its surface drag as function of water speed, and its weight per unit length. The trim of the HW housing is adjusted by the heavy brass nose so that the hydrophone tends to nose downward at low speeds, while the stability of the body and tail fin design tends to hold it on this course. This downward planing effect lets the HW reach considerable depths before the upward and downward forces become equal. With increasing speed this depth decreases, however, and ultimately the HW is pulled near the surface where whitecap noise interferes with the signal.

Tests indicate that the depth of the HW for a given length of cable is inversely proportional to the square of the speed. These measurements were made in preparation for using the HW in ship-sound studies, towed behind a destroyer. The reinforced cable of the final HW design was used, and a syphon-operated depth gauge replaced the crystal bank in a standard housing. A plot of the empirical relationship determined by these tests is shown in Figure 7 for two speeds.

The towing load on the cable depends to a first approximation upon the length of cable that is underwater. Where a great deal of cable is submerged, the surface drag, which is a function of speed, sets the maximum permissible towing speed. With 1,000 feet of cable underwater this limit was encountered at 14 knots when the cable covering was seen to fail.

An estimate of the towing life of the HW is based upon tests from a surface vessel where failures of one or more cable leads occurred near the nose of the hydrophone after 8 hours of towing at speeds of 12 to 14 knots. This failure repeated itself on 4 successive days, the respliced cable always breaking in the same place after approximately the same use. This implies that the yawing, although imperceptible, was significant in these conditions. The use of preformed aircraft cable in place of mild steel for the reinforcing strands was proposed as a remedy.

8.3 GENERAL CURVE FOR TOWING CABLES

A study was made of the shape of towing cable in both water and air to aid in predicting the depth of a towed body. A general curve was derived[1] to give horizontal trail distance against depth in dimensionless units. This permits conversion to any specific case by application of the proper scale factor. The cable curve and a plot of its slope are shown in Figure 8. The cable curve is the theoretically determined curve obtained from the summation of forces acting on the cable. The experimental points, as indicated in the figure, are derived from towing tests with cables in water at speeds from 2 to 12 knots and with cable in air at 100 knots. The agreement with theory is good in all cases.

This curve was obtained by letting the depth unit $Y = (ypd)/T$, where y is the depth in feet, d the cable diameter in feet, T the tension, and p the dynamic pressure. This dynamic pressure $p = \frac{1}{2}RV^2$ becomes a simple function of the speed V if R (Reynolds number) is taken as unity. Tests have shown this assumption to be valid in the range of speeds encountered in towing for the types of cable that were used. the horizontal trail distance unit $X = (xpd)/T$ was obtained similarly. In using this curve to compute the towing depth for a given body at a given speed, the observed slope of the cable at its entrance to the water is used to select a point A, as shown in the figure where the curve has the same slope. Computation of the forces acting at the point of attachment of the cable to the tractor or towed body determines the slope at the foot of the cable, and hence point B. The intervening shape of the cable can be taken from the curve without further calculations.

The points A and B shown in Figure 8 correspond to the case of a streamline body weighing 60 pounds in water towed on 600 feet of ¼-inch cable from a blimp. The speed was taken as 20 knots. With these quantities, a submergence depth of only 2.6 feet is indicated by the curve.

8.4 STATUS OF TOWED HYDROPHONE DEVELOPMENT

The satisfactory development of the *expendable radio sono buoy* [ERSB] led to termination of work by the NDRC on towed hydrophones as a means of underwater listening from patrol blimps. At the time neither the HW nor the blimp-towed hydrophone was reliable at the cruising speeds necessary for ordinary blimp operation. The evaluation tests made during the summer of 1945 corroborated this earlier estimate. Information gained about the towing performance of these streamlined bodies and about cable characteristics should be found useful if interest in this program is renewed.

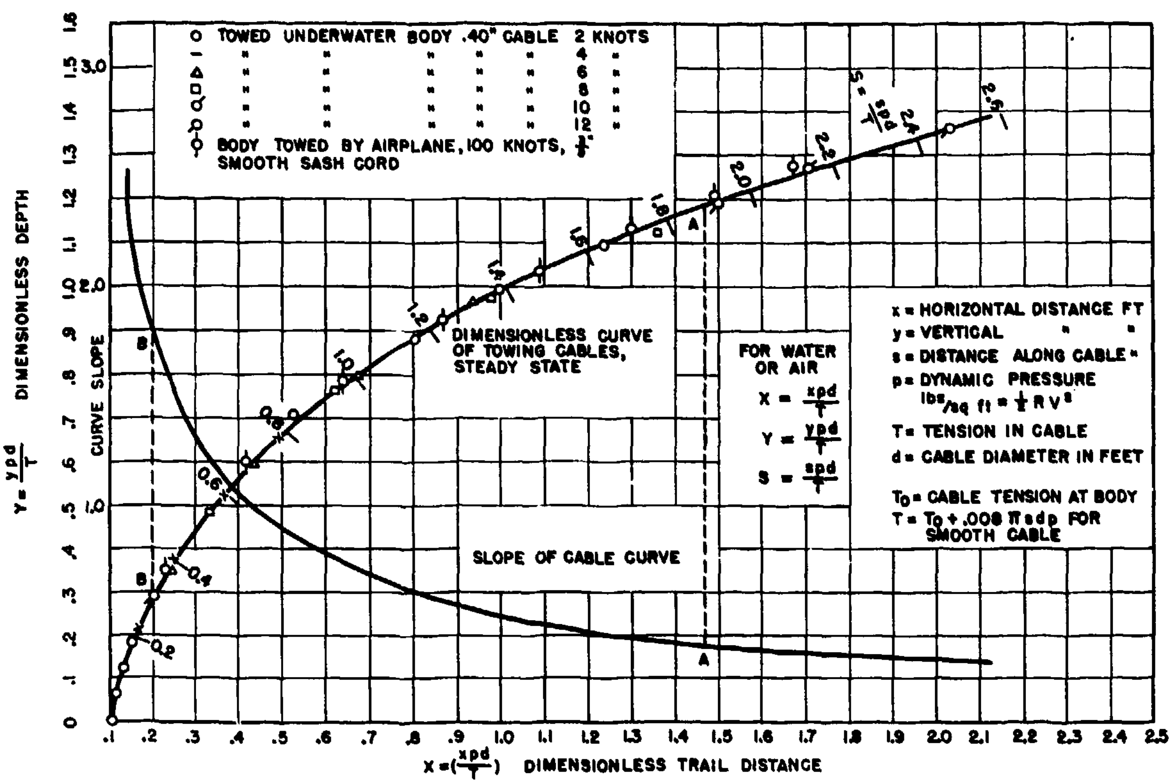


FIGURE 8. Dimensionless curve for towing cable in steady state.

Chapter 9

AIRCRAFT LISTENING EQUIPMENT—RADIO SONO BUOYS

9.1 INTRODUCTION

RADIO SONO BUOYS are devices designed to allow remote detection of sounds in the water. These sounds are picked up by a hydrophone and broadcast by radio to a receiving station located aboard a ship, in an airplane or blimp, or on shore.

A forerunner of the *expendable* and *directional radio sono buoys* [ERSB and DRSB] was an experimental convoy protection buoy developed by the Radio Corporation of America and designed to be dropped astern of the convoy. Its purpose was to detect trailing submarines in time to allow initiation of countermeasures against an attack. Although this buoy was not carried beyond the experimental stage, it was valuable as a basis for the preliminary design of the buoys discussed in this chapter. Another buoy that contributed to the design of the radio sono buoys was the *anchored radio sono buoy* [ARSB], intended for application to harbor defense. A brief description is included in Chapter 13.

Before the development of the expendable buoys, the *magnetic airborne detector* [MAD] (discussed in Volume 5, Division 6), provided the only method for submarine detection from aircraft; but its range is short (200 to 300 feet) and, because it detects wrecks as well as submarines, its indications are sometimes misleading. Therefore, when the tactical situation indicated increased use of aircraft in antisubmarine patrol, work on an expendable listening buoy to supplement MAD and to extend the range of detection was inaugurated.

The first device to be completed and put into operational service was the ERSB. Partial evidence of its effectiveness in the field can be gathered from the fact that more than 160,000 of the units were ordered. The original general requirements demanded that the buoy have a radio range of at least 5 miles, that it provide a continuous operating life of at least 2 hours, that it be light in weight and small in size, and that it be suitable for release from blimps by a lowering line or other simple means. Decision to use the buoy independent of MAD equipment and with heavier-than-air craft as well as with blimps brought up the additional problem of making the buoy suitable for launching from airplanes.

While the underwater sound range of the buoy is generally unpredictable because it is dependent on water conditions and on the maneuvers and evasive tactics of the target, submarine detection ranges of 2 miles or more may be expected under excellent conditions. An aircraft at an altitude of 5,000 feet has an effective maximum radio range of 35 miles.

With the ERSB, a submerged submarine can be kept under aural observation, oil slicks can be investigated, and damage to a submarine during attack can be more readily ascertained. It is also possible to track a moving submarine. For this function it is necessary to employ several buoys simultaneously—to lay them in a pattern and note the relative intensity and variation in intensity of the sound at the different buoys.

It was felt, however, that these functions could be more effectively performed if a buoy could be developed which would be capable of broadcasting not only the underwater sounds it might pick up but also the direction from which these sounds come. Tactical operations would be expedited, observation time would be reduced, and space in aircraft would be saved.

The idea of a directional buoy was conceived early in the radio sono buoy program. Therefore, when the major engineering problems of the ERSB had been answered, work on the DRSB was started. A directional hydrophone was substituted for the nondirectional ERSB hydrophone. This hydrophone rotates continuously to provide 360-degree scanning in a horizontal plane around the buoy. To provide bearing information, the frequency of the radio

transmitter varies with rotation of the buoy; the receiver is capable of interpreting this frequency variation in terms of bearing.

To accomplish these ends, it was necessary to redesign the several electronic circuits, to select a hydrophone with suitable characteristics, to devise a method for supporting rigidly and for rotating the hydrophone, and to develop a scheme for providing a reference direction to which rotation could be related. Furthermore, to obtain adequate directivity, a larger hydrophone than that in the ERSB was needed, and this, together with the mechanism needed to rotate the buoy, added appreciably to its weight and bulk. Therefore a general redesign of the buoy was required.

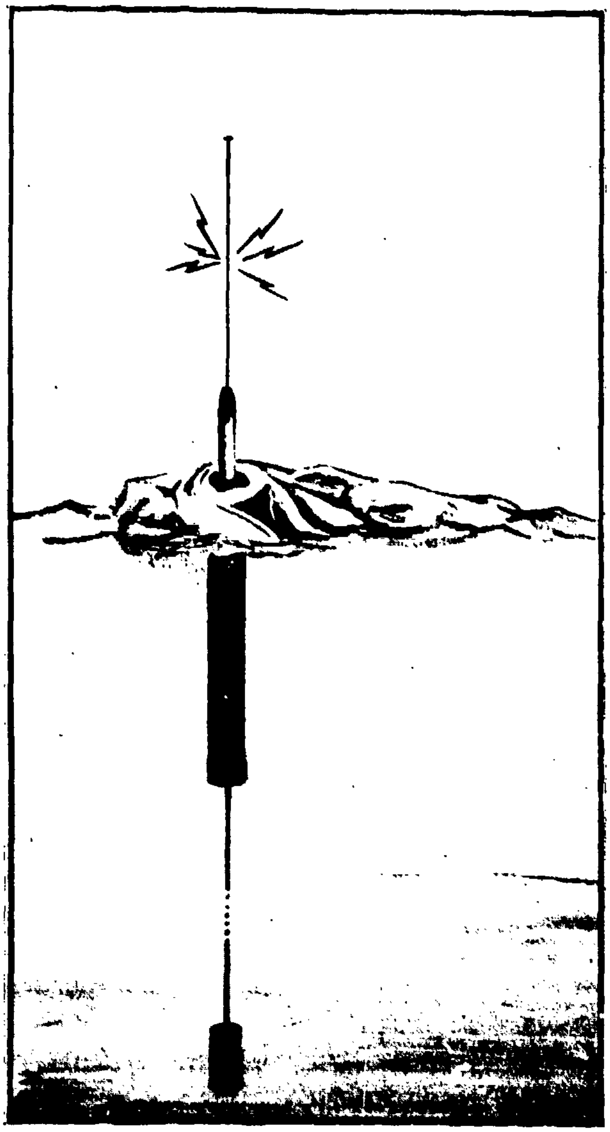


FIGURE 1. The expendable radio sono buoy [ERSB].

Although emphasis in the chapter is placed on the use of the ERSB and DRSB from aircraft, they were often launched from ships. The directional buoy was particularly well suited for this use because ship noise did not, generally, interfere with target-noise detection. Whether operated from aircraft or ships, both buoys played a major part in the listening program. The discussions in this chapter cover their uses, operation, performance, and reasons for their development along with suggestions for further development of this type of listening equipment.

Expendable Radio Sono Buoy [ERSB]

The ERSB, also designated by the Army-Navy type number AN/CRT-1A, is a device designed to be dropped from airplanes or blimps by means of a small, self-contained parachute and used to pick up the underwater sounds of submarines and transmit them to the aircraft by radio. It is made up of a cylindrical magnetostriction toroidally wound hydrophone and an amplifier connected to an f-m radio transmitter. The sonic hydrophone, amplifier, and transmitter, along with a battery power supply, are incorporated in a waterproofed cardboard tube about 30 inches long and 4 inches in diameter weighing approximately 12 pounds. The transmitter and batteries are housed in an upper compartment, separated by a watertight bulkhead from the hydrophone, cable, and release mechanism in the lower compartment. The transmitter operates on frequencies between 67 mc and 72 mc and has a maximum range of about 35 miles when the aircraft is at an altitude of 5,000 feet. The device has an operating life of 2 hours to 4 hours after planting, after which a Carbowax plug dissolves and permits the buoy to sink. In order to track a moving submarine, several buoys may be dropped in a pattern surrounding the known or suspected location of the submarine. A receiver designated by the Army-Navy type number AN/ARR-3 is carried in the aircraft. This receiver has up to 12 channels corresponding to the particular frequencies of a like number of buoys. A high degree of automatic frequency control [AFC] is

incorporated to compensate for any lack of frequency stability in the buoys. This equipment was developed by CUDWR-NLL. The Emerson Radio and Phonograph Company and the General Textile Mills furnished the manufacturing designs and the parachutes respectively.

9.2 EXPERIMENTAL WORK

Early Models

The basic requisite of an aircraft-launched buoy was considered to be a small, rugged, lightweight radio transmitter having low power consumption. After settling on the desirability of f-m transmission, a number of experimental models were constructed in rapid succession.

Mark I. The first transmitter model, Mark I, shown in Figure 2, was of single-deck construction and employed four battery-supplied vacuum tubes. This design met the requirements as to size, weight, and power consumption reasonably well but lacked sufficient a-f amplification.

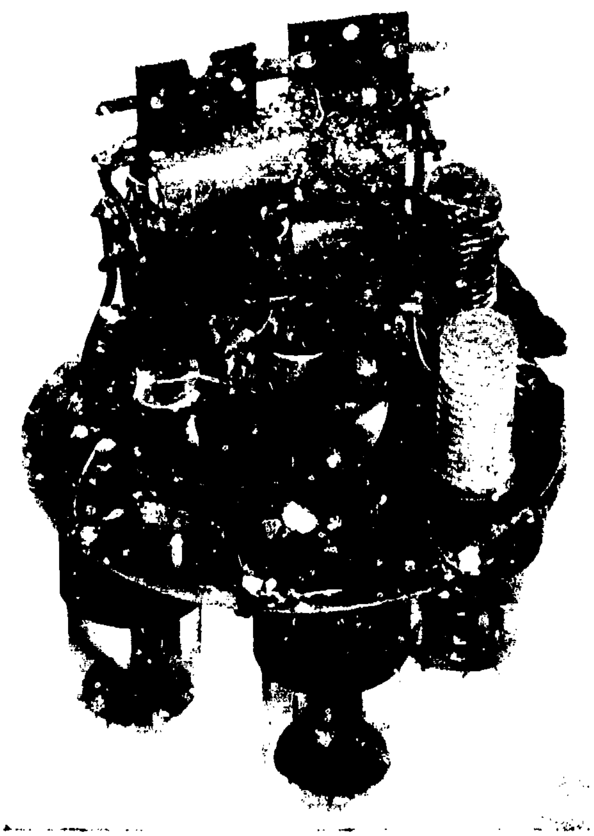


Figure 2. The Mark I experimental transmitter

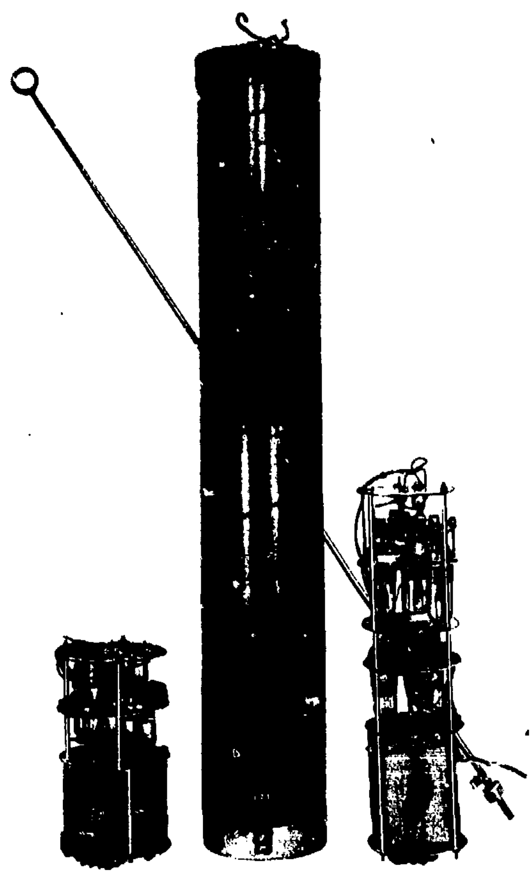


Figure 3. Mark II (right) and Mark III experimental transmitters with first experimental buoy (center).

Mark II. A redesigned transmitter employed five tubes mounted in a multiple-deck chassis with the r-f and audio circuits separated. This transmitter, together with a special magnetostriction hydrophone, was housed in a waterproof paper tube and provided with an antenna rod to make up the first complete unit, designated the Mark II buoy. In this model, shown in Figure 3, the hydrophone and its connecting cable were held in the lower portion of the housing by paper tape designed to break upon impact with the water and allow the hydrophone to drop to the limit of the cable. Four of these units were tested in free-fall drops

from a blimp of 100 and 200 feet, and although three of the four operated after reaching the water, their transmission was characterized by considerable carrier-frequency shift. Subsequent examination showed that some vacuum-tube elements had been bent by the shock of impact. These tests indicated the necessity for some means of decreasing the impact and insuring vertical entry of the buoy into the water.

Mark III. In an effort to solve the launching problem, a Mark II buoy was lowered from a blimp by a handline. The handline method proved so troublesome that it was promptly abandoned. A third design, Mark III, was equipped with a small parachute and was dropped from an altitude of 500 feet, suffering no damage. On the basis of these tests, this design was considered a satisfactory solution to the problem of launching the buoys from lighter-than-air craft. The Mark III design was abandoned, however, because its reduction in length was not accompanied by a corresponding reduction in diameter, and thus the buoy-housing tube did not have the length-diameter ratio necessary for stability in the water.

Mark IV. The final experimental model, Mark IV, employed a multiple-deck type of construction with the antenna coupling, radio-frequency, and audio-frequency circuits separated and arranged in order from top to bottom. In this buoy the upper portion of the housing was covered on the outside with a copper foil sheet which served as an electrostatic shield. The parachute, attached to a ring at the top of the antenna, disengaged automatically when the buoy came to rest in the water. Successful tests of the Mark IV resulted in development of a model more adaptable to production, the Mark IV B, of which small lots were ordered for further tests.

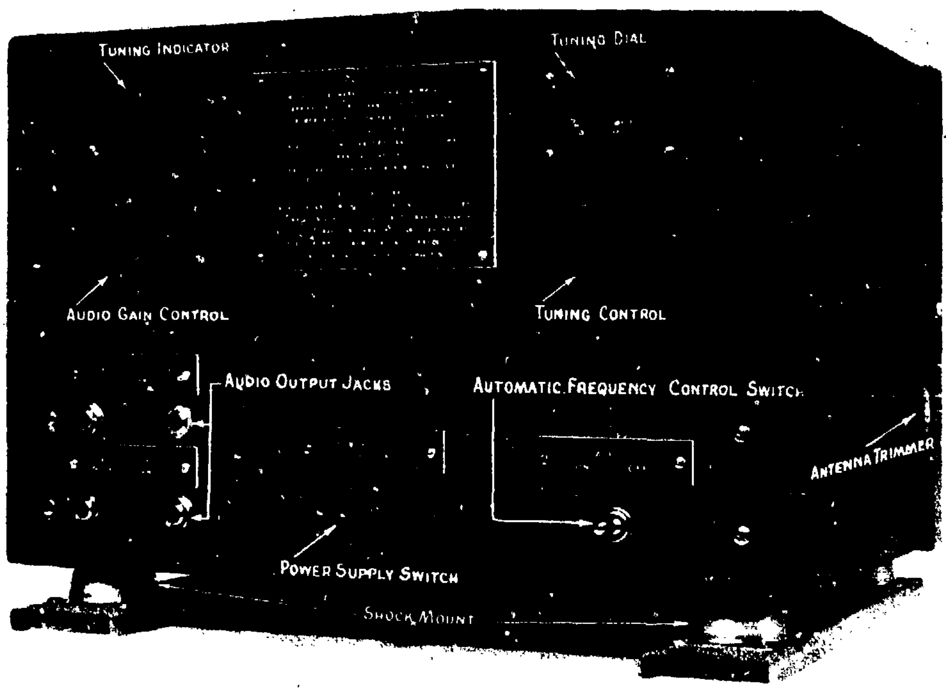


FIGURE 4. Prototype (Mark II) receiver

Mark IV C. The development work up to this time had been directed solely toward production of a buoy which could be launched from blimps, although it had early been realized that launching from airplanes might eventually be desired. For this reason, test launchings from airplanes were made to determine the

feasibility of adapting the Mark IV B model for use from heavier-than-air craft. These tests indicated the need for an improved parachute as well as certain other mechanical changes to make the unit suitable for launching at higher speeds. Further tests, using a redesigned parachute arrangement with the shrouds attached directly to the buoy top showed that a nearly vertical fall of the buoy, and thus better placement accuracy, could be attained. This model, with the redesigned parachute, was designated the Mark IV C. It was considered satisfactory for launching from all types of aircraft and orders were placed with a manufacturer for a preproduction lot of these units for operational and service tests in the field.

Mark IV D. Further improvements, directed largely toward facilitating storing and handling of the buoy, were incorporated in a still later model, the Mark IV D. The changes included the provision of a permanently mounted telescoping antenna, a compact parachute pack, an improved battery switch, and minor alterations in the a-f and r-f circuits aimed at increasing the uniformity of transmission characteristics. A preproduction lot of this unit was also ordered.

Production Model (AN/CRT-1) Buoy

Extensive service tests of the preproduction buoy models indicated that the development had progressed to a stage which justified quantity production to meet pressing needs. Specifications were drawn for a Mark IV E design incorporating a compact battery assembly using standard cells, a further improved hydrophone release mechanism, and a new, rigid, humidity-resistant and fungus-proof parachute pack. These specifications were used in manufacturing, first for the Army and then for the Navy, substantial production quantities of the Mark IV E buoy later designated by the Services as the AN/CRT-1 unit.

Mark II (Prototype) Model Receiver

The receiver used in the early buoy tests was of conventional FM design in most respects, but of small size and weight and with a wide-range AFC system capable of compensating for carrier frequency shifts of as much as ±200 kc. On the basis of tests in which three-buoy patterns were used, this receiver was designed to accommodate three frequency channels, but later tests indicated that patterns of four buoys were sometimes more effective. For this reason, and in anticipation of even more extensive future requirements, the receiver was redesigned to provide for six channels. The new receiver design, known as Mark II and shown in Figure 4, served as a prototype for the Service-designated AN/ARR-3 receiver which was put in production.

FIGURE 5. Type AN/CRT-1 and AN/CRT-1A buoys.

9.3 FINAL PRODUCTION DESIGN

9.3.1 AN/CRT-1A Buoy

With the AN/CRT-1 buoy and the AN/ARR-3 receiver in substantial quantity production approximately 9 months after the start of the development, further, more deliberate work was directed toward redesigning the buoy for improved performance and greater production economy. Extensive service use of the earlier buoy models indicated the need for redesign work to eliminate vacuum-tube microphonics. The new unit, evolved as a result of this development, had improved electric characteristics, including greater sensitivity and the elimination of microphonics. It also achieved the objectives of reduced weight, size, cost, and greater ease of production. This buoy became the prototype for the final production model, type AN/CRT-1A, which was manufactured in large quantities. The AN/CRT-1 and AN/CRT-1A buoys are compared in Figure 5.

HOUSING

The buoy housing consists of a convolute-wound Kraftboard tube, approximately 30 inches long by $4\frac{1}{4}$ inches in diameter, separated by a watertight bulkhead into an upper compartment for transmitter and batteries and a lower compartment for the hydrophone, cable, and release mechanism. The cutaway picture in Figure 6 shows this construction. A wooden cap, fitted with a rubber gasket and clamping screws, seals the top of the tube and serves as a mounting for the antenna and parachute assembly. This cap contains a soluble Carbowax[a] plug to sink the buoy for security after several hours' operation. Four $\frac{7}{8}$-inch holes are cut through the tube wall at the upper end of the lower compartment to insure flooding and to provide a cushioning effect by regulating air release as the buoy strikes the water. The upper part of the tube is sprayed on the outside with atomic copper to form an electrostatic shield; the whole tube is coated inside and out with a water-resistant compound.

[a] Carbowax is the trade name of a hard, opaque, nonhygroscopic polyethylene oxide solid having a melting point above 135 F.

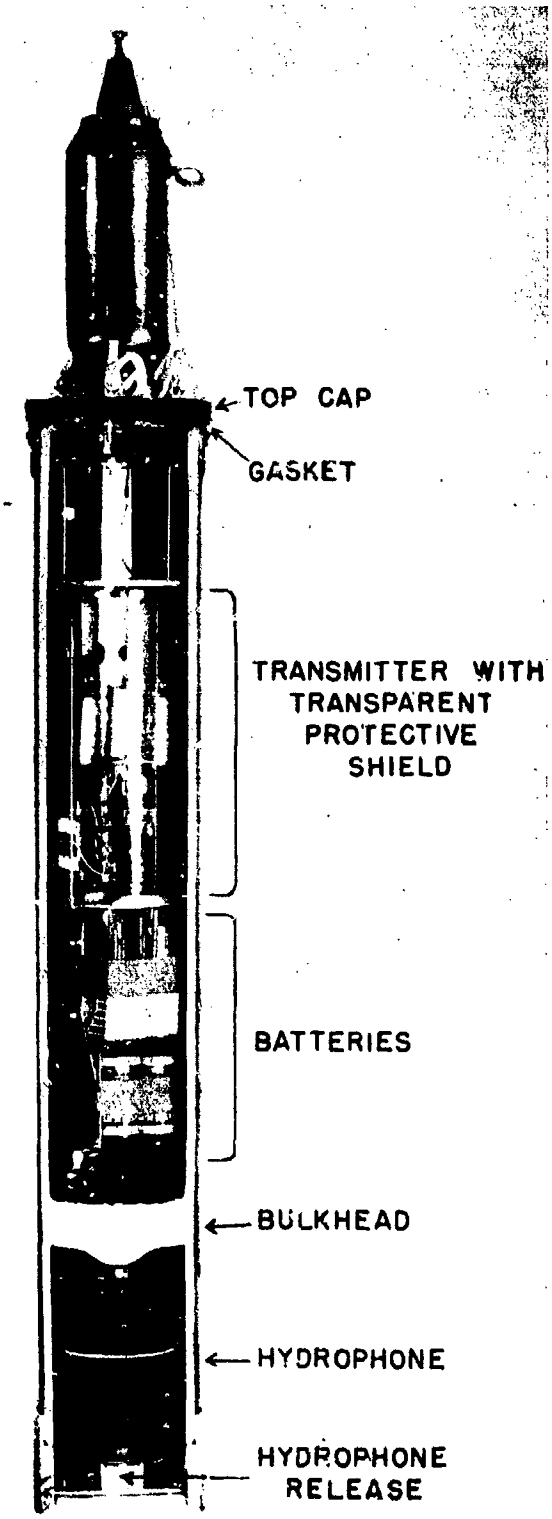


FIGURE 6. Section view of AN/CRT-1A buoy.

Hydrophone Release Mechanism

The bottom end of the housing terminates in a cast metal ring which aids in stabilizing the buoy in the water and provides a mounting for the hydrophone release mechanism.

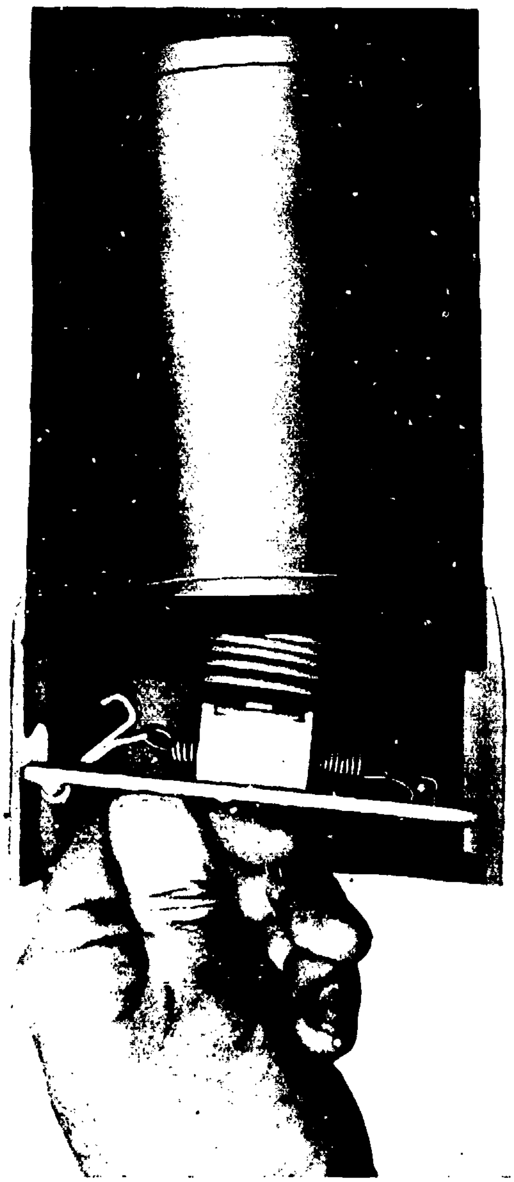


FIGURE 7. Hydrophone release, triggered as at moment of impact with sea.

This mechanism, illustrated in Figure 7, consists of a spring arrangement which holds the hydrophone firmly in place during shipping and handling but which automatically triggers on impact with the water and permits the hydrophone to drop to the limit of its 24-foot cable.

Hydrophone

The hydrophone, shown in Figure 8, is a cylindrical magnetostriction unit, toroidally wound directly on a nickel shell. It represents a new design first applied to sono buoy use in the AN/CRT-1A model. This construction permits storing of the cable inside the hollow shell and effects a reduction in length of nearly 4 inches compared with the more conventional magnetostriction unit used in earlier models. In addition the hydrophone yields greater effective voltage at the input of the first tube and has more uniform operating characteristics. The family of frequency-response characteristics, shown in Figure 9, rises sharply with increasing frequency, complementing the reverse type of characteristic typical of submarine sounds and inherent sea noise, and hence providing a substantially flat overall modulation voltage.

Transmitter

The FM transmitter utilizes five vacuum tubes providing approximately 90 db of audio-voltage gain and an effective r-f antenna radiation of about 0.1 watt. Frequency modulation was used in preference to amplitude modulation for three main reasons: (1) Its signal-to-noise ratio was considered of vital importance because the receivers are always used in close proximity to aircraft engines, with the attendant possibility of ignition interference; (2) it provides precise automatic control of volume of all signals sufficiently strong to fall within the effective operating range of the receiver; and (3) it eliminates interference between two buoys of the same color frequency. This applies when extra buoys are dropped, in tracking, before the original buoys have ceased operating.

The AN/CRT-1A, in contrast to the earlier buoy transmitters with multiple-deck type construction, employs a single, rectangular plate, mounted vertically, with the audio amplifier and the reactance tube on one side, and the r-f

circuit on the other. Compactness and improved isolation between the a-f and r-f circuits are thus achieved, as indicated in Figure 10. Freedom from microphonic noise is achieved by use of four shockproof rubber mountings for the chassis plate as well as separate rubber mounting for each tube socket. This eliminates the necessity for the undependable and expensive process of tube selection. The vacuum tubes are provided with locking-type shields to prevent their being loosened by the jarring to be encountered in shipment, impact, or use, and the whole transmitter assembly is enclosed in a transparent acetate tube for protection when withdrawing the unit from the housing for installation of batteries.

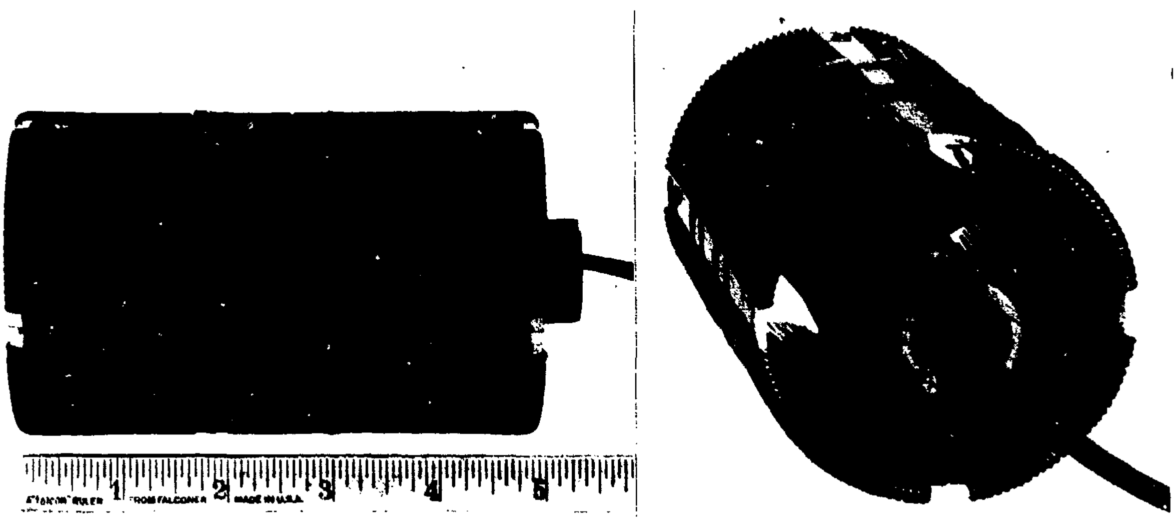


FIGURE 8. Toroidally-wound CRT-1A hydrophone. Plastic inner structure protects cable connection and provides means for supporting the hydrophone within the buoy.

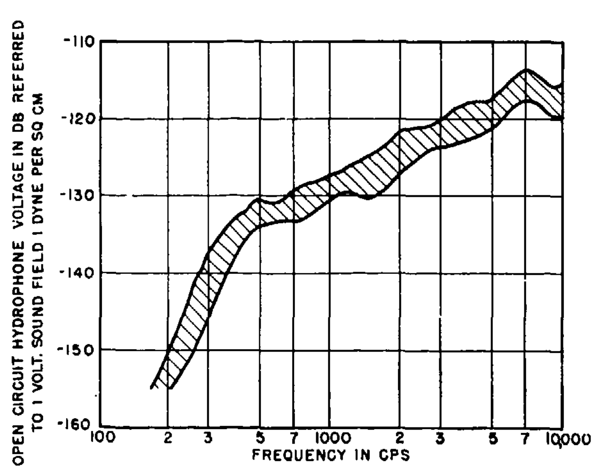


FIGURE 9. Frequency response of fifteen CRT-1A hydrophones.

A schematic circuit diagram of the AN/CRT-1A transmitter is given in Figure 11. By substituting pentodes for triodes, a change was made from three a-f amplifier stages to two, with resultant decrease in the number of circuit components over the earlier sono buoy designs. Use of permeability tuning in three of the four r-f tank circuits simplified the production process because the type of adjustment required is less critical than that necessary with the variable capacitors that had been used formerly. This type of tuning is also less sensitive to the shock of impact or rough handling and so provides increased frequency stability.

BATTERY SUPPLY

The battery assembly consists of four standard 1.5-volt flashlight cells in parallel for the filaments, and two series-connected 67.5-volt miniature B batteries for plate voltage. Sufficient battery capacity is available for a continuous operating life of approximately 4 hours.

Antenna

The antenna is a 39-inch telescoping quarter-wave tube mounted on the buoy housing cap with 9½ inches of its base enclosed in a watertight insulating sleeve to avoid short-circuiting by waves. It is coupled to the r-f amplifier tube by a tuned circuit which matches the impedances of the antenna and transmitter and helps to stabilize operation. It accomplishes the latter by isolating the tuned transmitter circuits from the direct influence of any variations in antenna characteristics due to motion of the buoy.

Parachute

The parachute, 24 inches in diameter, is of muslin, dyed orange for increased visibility. Its shroud lines are attached to the buoy cap. During shipping and storage it is contained in a moisture-resistant pack fitted around the insulating sleeve at the base of the antenna. After launching, the pack cover is torn loose by a static line attached to the plane, the parachute blossoms around the extended antenna which protrudes through a 3-inch hole in the top (Figure 12), and the pull on one of the shrouds withdraws a switch pin and so turns on the

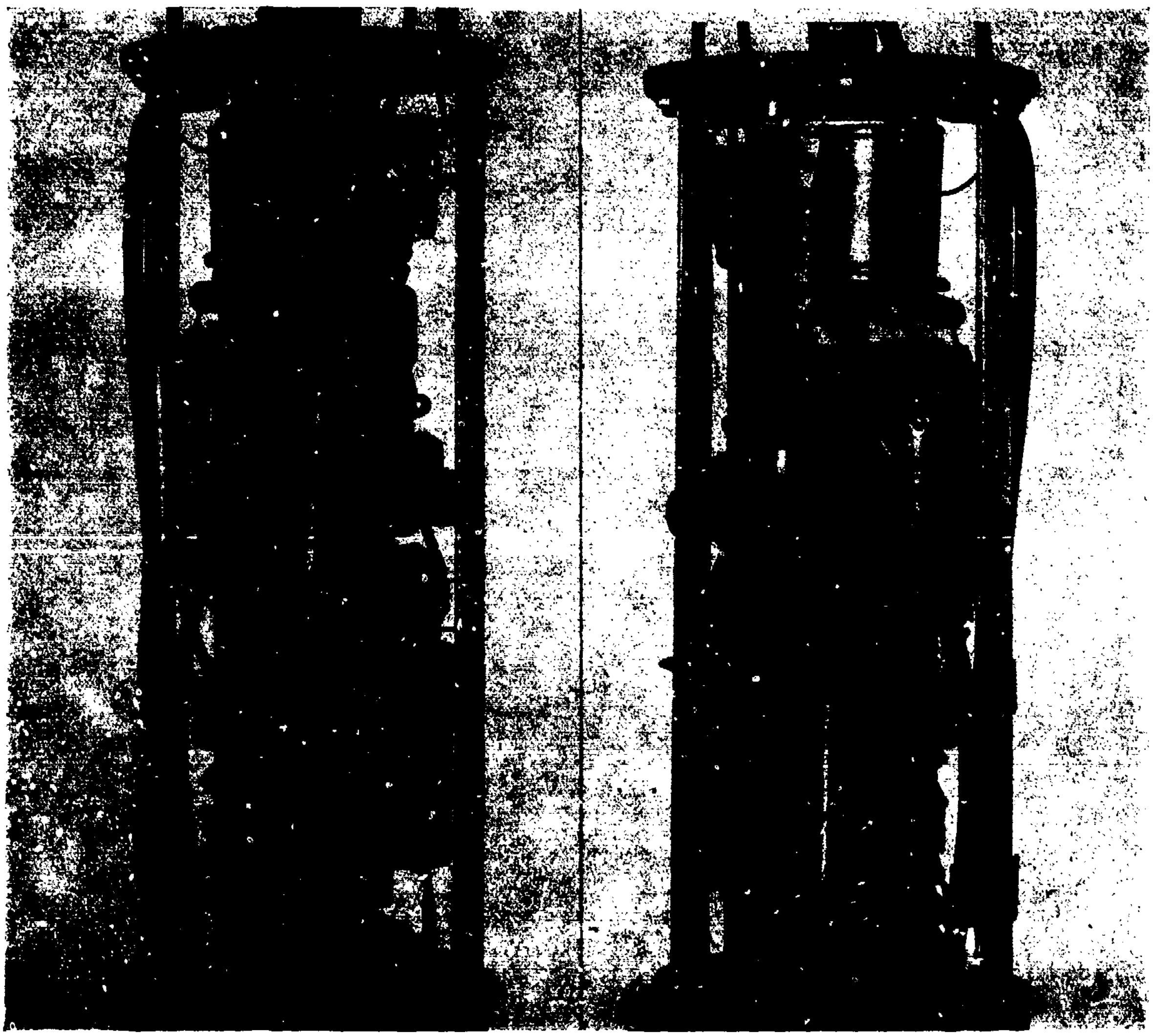


Figure 10. R-F (left) and A-F sides of CRT-1A transmitter.

transmitter. As the buoy reaches the surface after its initial plunge into the water, the parachute settles around the antenna base.

9.3.2 AN/ARR-3 Receiver

The AN/ARR-3 buoy receiver is a 13-tube superheterodyne type, shown in Figure 13 and schematically in Figure 14. It provides for the reception of frequency-modulated signals in

This AFC feature is necessary since the transmitter carrier frequency goes on the air from a cold start and its stability is likely to be affected by such factors as decreasing battery voltage, severe mechanical shock, and sudden temperature changes. A feature of the AFC which was beneficial in the field was the ease of tuning it gave, since the pattern technique requires continual switching from one buoy to another.

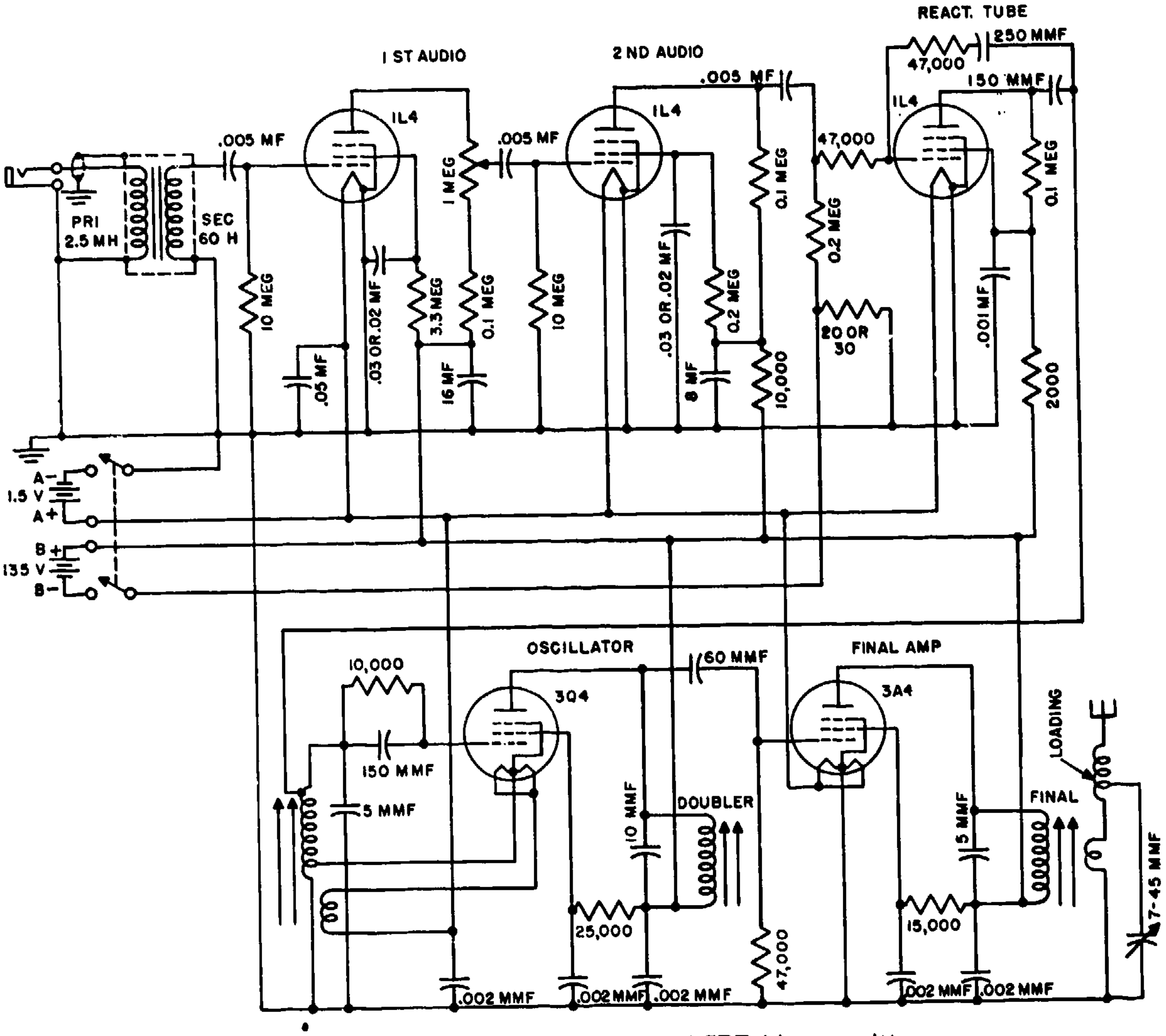


FIGURE 11. Schematic circuit diagram of CRT-1A transmitter.

any of six channels covering the range 67.2 to 72.2 mc, and incorporates an automatic frequency control [AFC] system capable of shifting the local oscillator sufficiently to compensate for carrier-frequency drift up to ± 200 kc.

The AFC is accomplished by means of a control voltage which is developed in the discriminator stage and fed back to the control grid of the phase amplifier tube. This tube, in turn, through the oscillator-control tube, regulates

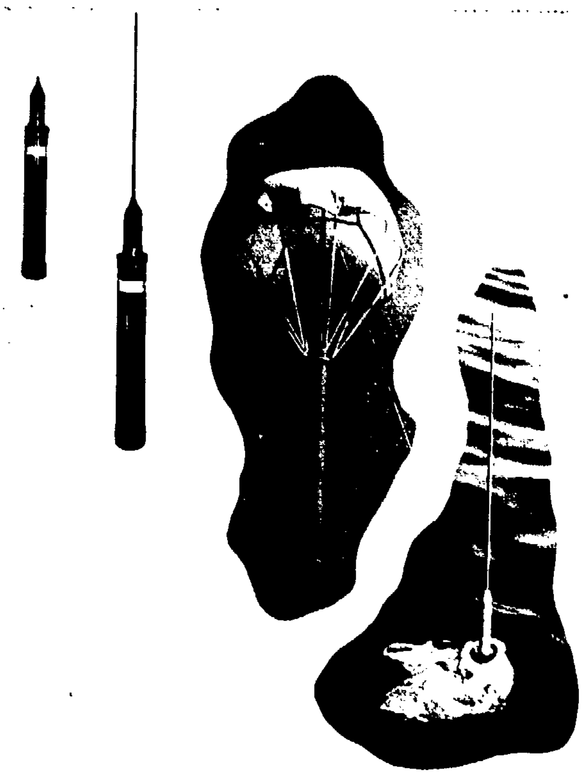


FIGURE 12. ERSB during launching.

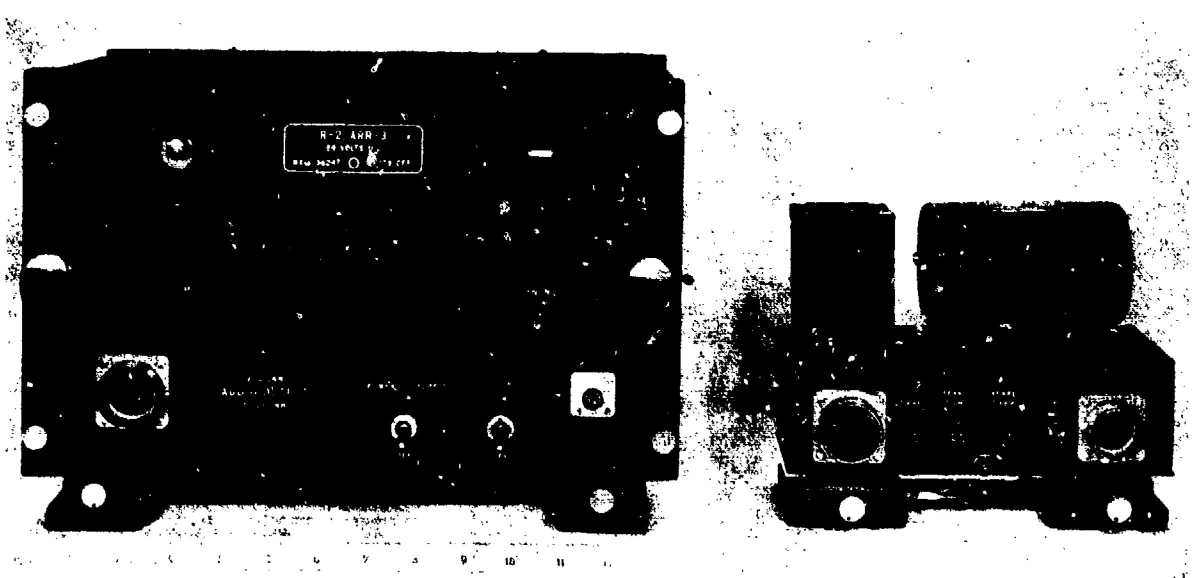


FIGURE 13. Type AN/ARR-3 receiver and power supply.

the amount of out-of-phase current or reactive load that is reflected across the tank circuit of the local oscillator and causes its frequency to change as necessary to compensate for the amount of carrier-frequency shift. The delayed-action time constant of this circuit is sufficient to avoid interference with the reception of signals that deviate ± 75 kc even when the variation is at as low a frequency as 50 c. When it is desirable for purposes of checking the buoy transmitter frequencies, the AFC feature can be cut out by means of a switch on the receiver panel.

Additional operating characteristics of the receiver include a measured sensitivity of from 8 to 12 μv for 20 db quieting, a minimum image rejection of 49.6 db, and an a-f response flat within 5 db between 100 and 10,000 c. Each unit is provided with a separate dynamotor power supply which uses a 24-volt source.

In other respects, the circuit of the AN/ARR-3 receiver follows conventional FM design. It utilizes two r-f stages, the first untuned (trimmer-adjusted at the time of installing the receiver), the second tuned by one section of the three-gang condenser, operated by the tuning control, whose other two sections tune the oscillator and mixer stages. The i-f amplifier, with a pass band of 150 kc centered at 5,000 kc, consists of three stages, one of which is a limiter. This is followed by a discriminator and a two-

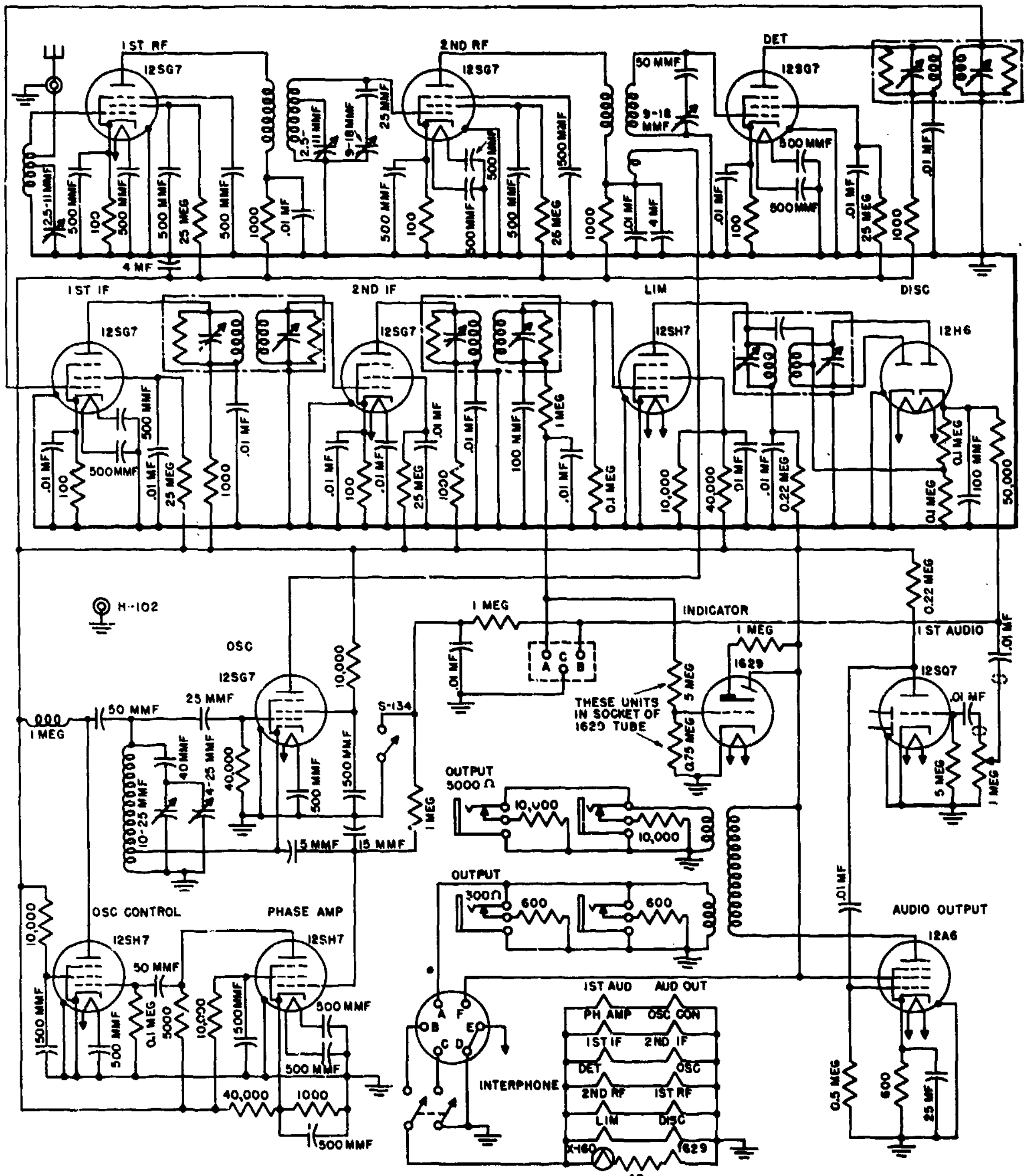


FIGURE 14. Schematic circuit diagram of ARR-3 receiver.

stage a-f amplifier. Outputs of 300- and 5,000-ohm impedance are provided to accommodate electromagnetic or crystal type headsets.

Sections of the tuning-control dial, corresponding to the frequency bands of the operating channels of the buoys, are colored to match the frequency-identification colors on the individual buoys and thus assist the operator in identifying the particular buoy to which he is listening.

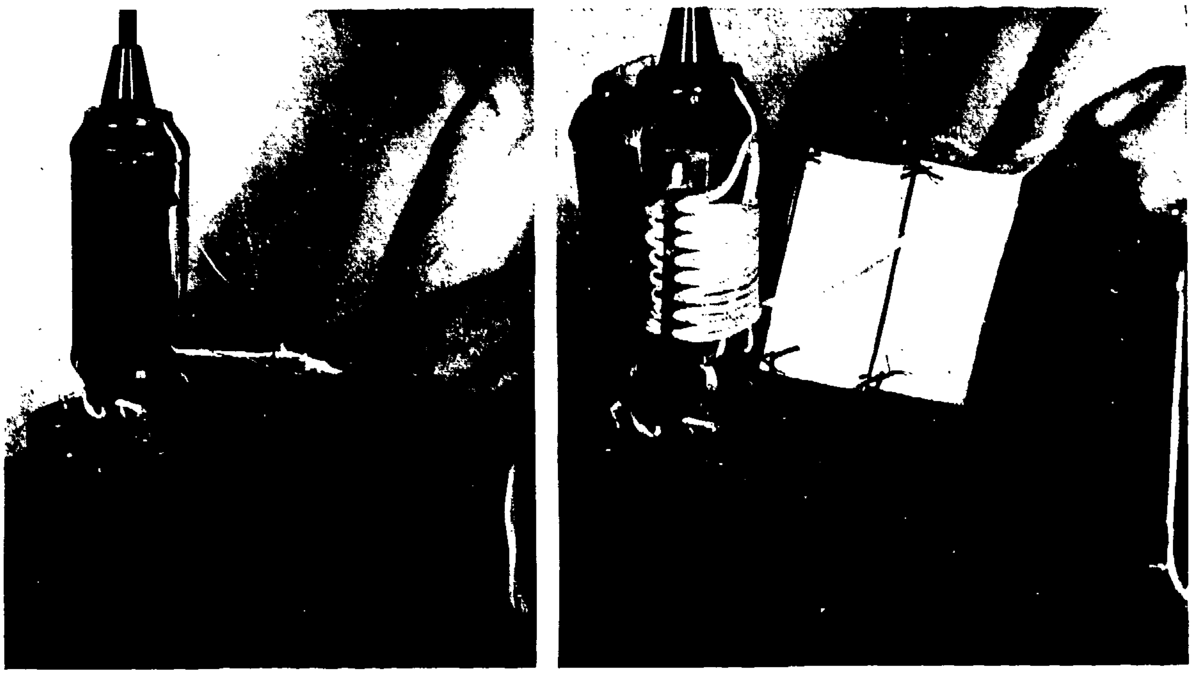


FIGURE 15. ERSB before launching: (A) Withdrawing static line removes soluble seal protector plug. (B) A1-0 seal and cardboard covers ripped and removed. Static line is then tied to airplane.

9.4 OPERATION OF EQUIPMENT

TESTING

At operational bases each buoy is given a performance test in which the antenna current is measured or the actual radio signal is checked with a field-strength meter. In addition, the frequency adjustment of the transmitter and the performance of the hydrophone and audio system are checked by means of a calibrated AN/ARR-3 receiver using the buoy hydrophone as a microphone to pick up speech or tapping sounds. Similar tests are repeated just before the buoys are placed in aircraft for use and, if possible, a quick listening check is made just before launching.

LAUNCHING METHODS

The buoys are commonly launched in one of three ways, by hand through an open hatch, by means of a built-in launching tube, or automatically from the bomb bay. In hand launching, the buoy is first prepared by removing the protective packing and extending the antenna. Next, a few feet of static line are pulled out. This operation withdraws the rubber protector from the hole containing the soluble plug. Then the moisture-resistant and outer cardboard parachute covers are ripped off. These procedures are illustrated in Figure 15. The end of the static line is then secured to the plane, and the buoy, with its antenna pointing down and aft, is thrust out through the hatch. After a 20-foot free fall which pays out the balance of the static line, the end of the line rips the last paper cover from the parachute, permitting the chute to open, and a weak link parts, leaving the line attached to the plane. The blossoming parachute causes one of the shrouds to actuate the switch which sets the buoy transmitter in operation.

In planes equipped with a launching tube, the sequence of operations is the same as in hand launching except that the buoy is ejected by an elastic cord when a holding device is triggered. In bomb-bay launching, the buoys are attached to the bomb shackles by means of metal straps, and the entire launching procedure, except for extending the antennas and tying the static lines before placing the buoys in the racks, is automatic. This method has the advantage of permitting several buoys to be kept in constant readiness for dropping in quick succession if

desired and permits attachment of dye or other markers directly to the buoys.

Slicks and Markers

Since the buoys are not easily seen from the air, several methods of marking their location have been developed. In the daytime, metallic or dye slicks and float lights, giving off both smoke and flame, are used. Since the metallic bronze and aluminum slicks have generally too short persistence except in very calm seas, and the Mark V float light[b] lasts only about 15 minutes, fluorescein and rhodamine dyes were favored. From an altitude of 3,000 feet, fluorescein is visible from at least 10 miles. Although rhodamine is visible from only about 5

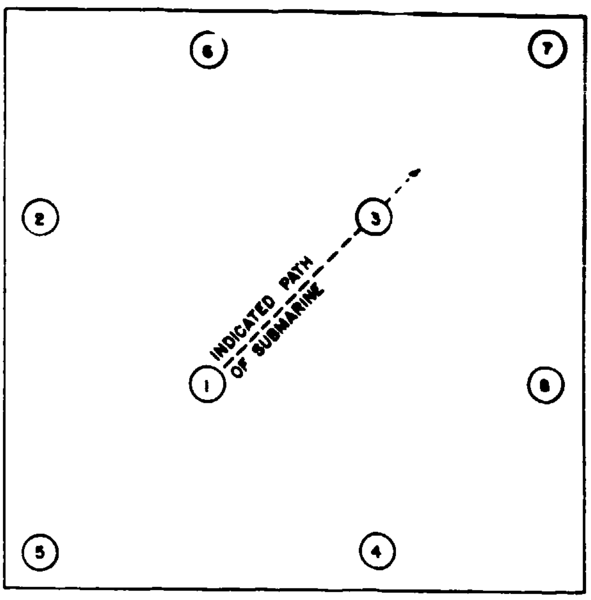


Figure 16. One type of pattern employed in buoy operation.

miles, its visibility is good on dull days. At night, the Mark V float light was found to be the best available means of marking the buoy locations.

Search Procedure

The buoys are used either singly, to investigate irregularities such as oil slicks, disappearing radar blips, and MAD indications or in patterns for tracking submarines. In the latter application, five buoys are usually laid in a square 2 miles on a side, with one unit at the center marking the best estimate of the submarine's location. By successive switching among the five buoys, the path of the submarine can be traced through changes in the relative intensity of the sound from the different locations. If the submarine passes out of the pattern, a new square is started, as indicated in Figure 16, by dropping three more buoys, using as a center the one from which the most intense signal was obtained. Since these tactics may involve use of more than six buoys, a plan for increasing the number of channels to 12 has been considered and implemented as a means of preventing confusion which might arise in spite of the ability of FM circuits to select the strongest signal.

SUGGESTED IMPROVEMENTS

In large-scale use, the ERSB has proved to be an effective aid to antisubmarine warfare. Official reports indicate that the information supplied by these buoys has been largely responsible for establishing and maintaining contacts that have led to the destruction of enemy submarines on many occasions. It is believed, however, that a number of improvements would make the device even more effective. Foremost among these is the provision of directional indications to permit much more accurate location of submerged targets, longer listening ranges, and the use of fewer buoys.

In addition to the directional feature, it is considered desirable to double the number of frequency channels for the nondirectional buoys, to provide for connecting the receiver output directly into the plane's intercommunication system, and to develop containers for marker dyes which will dispense the dyes on impact with the water but which will not break in shipping or normal handling. The means of providing for the extra frequency channels and connection to the intercommunication system have received attention since the AN/CRT-1A buoy and AN/ARR-3 receiver were put into production. These modifications have been incorporated in the subsequent production models.

[b] Discussed in Division 6, Volume 18.

FIGURE 17. The directional radio sono buoy as it appears in the water.

Directional Radio Sono Buoy [DRSB]

The DRSB is a buoy that may be dropped from aircraft by means of a small parachute and is used, like the ERSB, to pick up the underwater sounds of submarines and transmit the sounds to the aircraft by radio, at the same time indicating the direction from which the sounds are arriving. It consists of a directional sonic listening hydrophone, sonic amplifier, rotating mechanism, and an f-m radio transmitter. The whole system is incorporated in a tubular buoy about 52 inches long, 6 inches in diameter, and weighing approximately 30 pounds. The container is composed of two tubes attached end to end. The upper one, a watertight buoyancy chamber, contains the radio chassis and batteries; the lower holds the folded hydrophone and the motor mechanism. Transmission of directional information is accomplished by means of a compass-capacitor which causes the frequency of the radio transmitter to vary with rotation of the buoy. A receiver, carried in the aircraft, is provided with a circuit to translate changes in the transmitting frequency into directional indications, shown on a meter. These buoys were developed by CUDWR-NLL.

9.6 PRELIMINARY DEVELOPMENT

It was early envisioned that the DRSB should employ a unidirectional hydrophone which would be rotated continuously and thus provide 360-degree scanning. To provide bearing information it was planned to vary the FM transmitter's carrier frequency with rotation of the buoy by connecting into the tank circuit of the oscillator a variable condenser so arranged that one plate would be held stationary while the buoy rotated. At the receiver end, the drift of carrier frequency would be indicated on the face of a zero-center voltmeter so connected as to show variations in the voltage applied to the automatic frequency control section of the receiver as the carrier varied from its prescribed frequency. The detailed methods of accomplishing these functions required considerable experimentation.

SELECTION OF A HYDROPHONE

In selecting a suitable hydrophone it was necessary to consider both its acoustic characteristics and its general mechanical adaptability.

Extensive tests resulted in agreement among observers that a 2-foot straight magnetostriction-type hydrophone was definitely superior to all others tested.[1] Because it provided the best bearing accuracy and range, it was adopted despite its somewhat greater size and weight.

HYDROPHONE SUPPORT

The support for the hydrophone and motor must be torsionally rigid and noise-free. After trying and discarding various types of flexible shafting and cable, it was found that telescoping metal tubing could be designed to meet the requirements. Although this type of coupling limits the practical depth at which a hydrophone can be suspended, it was used on all DRSB models.

ORIENTATION REFERENCE SYSTEM

Two means were investigated for providing a reference direction to which hydrophone bearing could be related. One of these made use

of the direction of the wind. A frequency-deviating capacitor was coupled to a wind vane mounted on the exposed portion of the antenna. This method worked but was erratic in a puffy wind. For this reason and because of the necessity for knowing wind direction at the airplane, this scheme was abandoned.

The second method involved the use of a liquid compass to give bearings with respect to magnetic north. The compass card was replaced by an eccentric metal disk which, together with a fork straddling the disk, comprised the frequency-deviating capacitor. The orientation of the metal disk was held constant by action of the earth's magnetic field. This compass-capacitor proved to be quite reliable and was incorporated in all models of the DRSB.

Methods of Rotating the Hydrophone

A number of methods for rotating the hydrophone were investigated. Those involving the use of wind action, wave action, electric power, compressed air, and coiled springs were considered and abandoned. A fairly satisfactory rubber-band motor[1] was constructed and actually used in some of the early experiments with dummy buoys. However, a gravity-type motor proved to be most suitable. This consisted of a spool of cord attached to the buoy and a weight arranged so that as the weight fell away from the buoy the spool of cord would unwind and rotate the buoy and hydrophone with respect to a set of water reaction blades. The weight falls approximately 100 feet for each hour of buoy operation. All complete DRSB models used this type of motor.

9.7 DEVELOPMENTAL MODELS

Mark I Buoy

The first DRSB model to be launched from aircraft was designated Mark I. It was housed in a paper tube 6½ inches in diameter by 38½ inches long, and weighed 22 pounds complete. A parachute eased its drop and guided it vertically into the water. Upon impact with the water, the antenna erected, the parachute cast off, and the hydrophone and motor dropped to the end of the telescoping support tube.

Figure 18 shows the top assembly removed from its housing to disclose the shock-mounted transmitter, battery supply, and compass-capacitor. Above the top deck is the parachute compartment. The transmitter was a non-

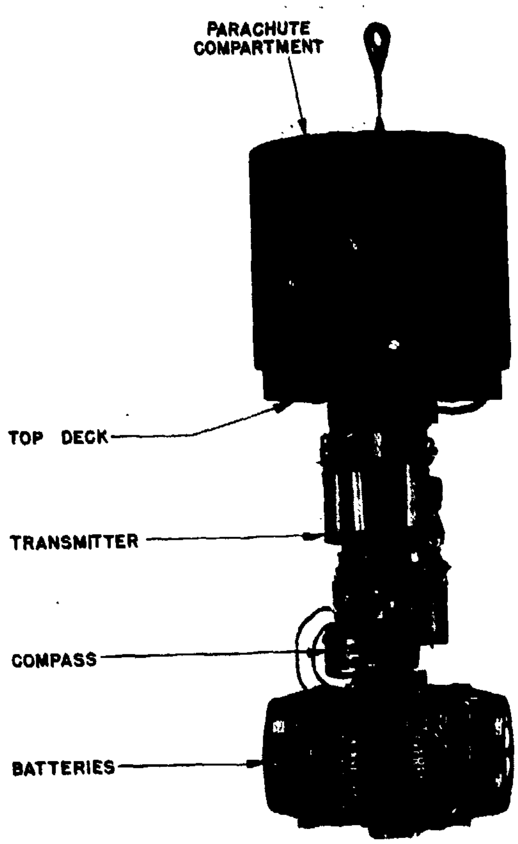


FIGURE 18. Top section, removed from housing—Mark I buoy.

magnetic modification of the AN/CRT-1A f-m transmitter described earlier in this chapter in connection with the ERSB. The compass-capacitor was of the double-pivot type, developed for the purpose and notable for its compact size. The antenna consisted of a set of telescoping metal tubes which collapsed into the transmitter chassis. Impact with the water actuated a spring release which erected the antenna and cast off the parachute.

The bottom end assembly with components folded to fit into the buoy housing is shown in Figure 19A. The two 1-foot sections of the hydrophone appear folded upwards, one section on each side of the telescoped support.

Below are the two flexible reaction paddles coiled around the gravity motor. On striking the water this unit drops out of the buoy housing, the telescoped metal tubing extends to its full length, and the hydrophone and paddle blades unfold into operating position as shown in Figure 19B. The metal base plate of the buoy serves as the weight for the gravity motor.

Tests on Mark I revealed the need for further improvements, especially in mechanical design of some of the components. Rough water caused erratic action of the small compass; even in calm water, bearing accuracy was only about 20 degrees. The hydrophone release and the antenna-parachute release mechanisms did not always function. Trouble was also encountered in the proper functioning of the parachute.

In efforts to improve antenna behavior, a spiral of springy metal ribbon was tried as the antenna. Extended, it took the form of a slightly tapering tube; compressed, it resembled a clock spring in shape. However, the release mechanism proved to be undependable.

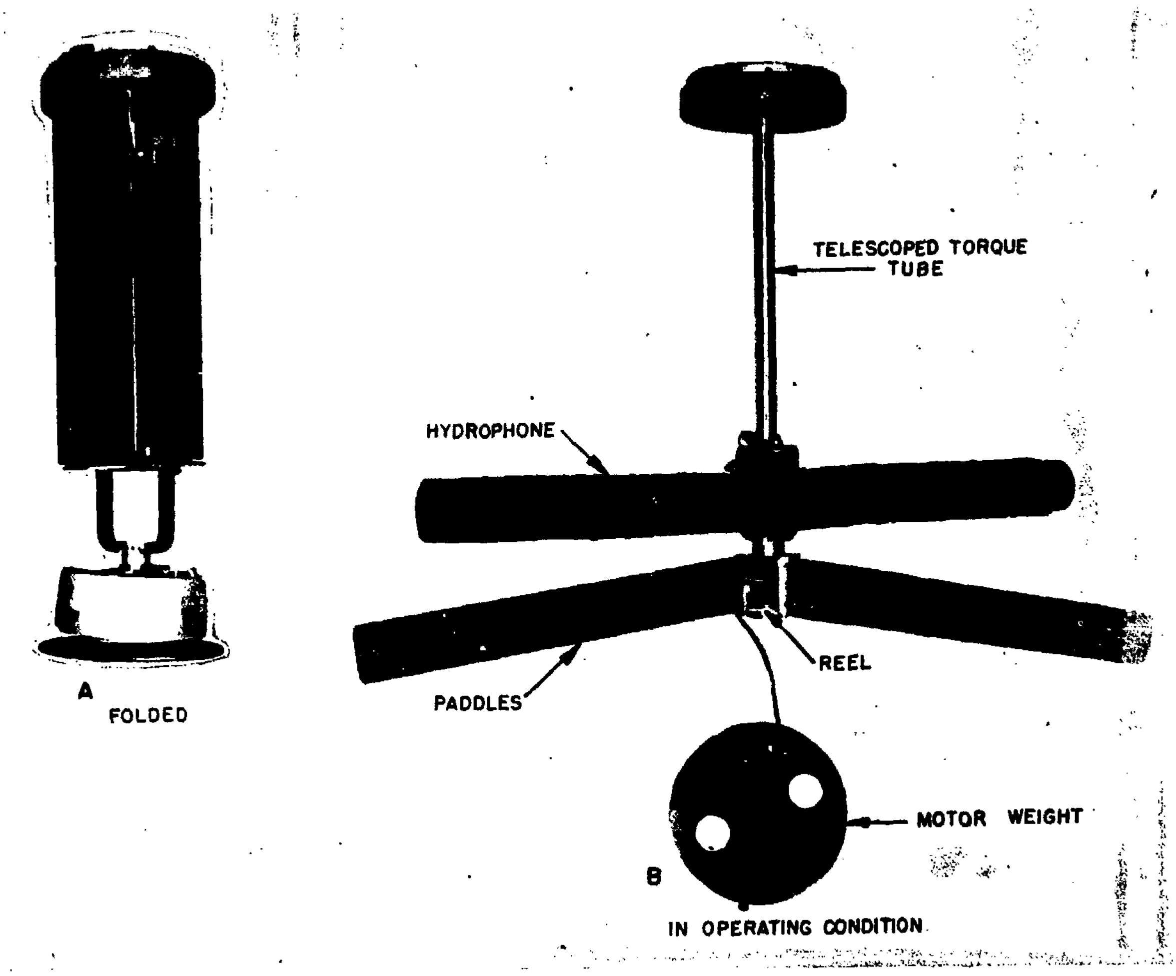


FIGURE 19. Bottom assembly of Mark I buoy. (A) folded; (B) operating position.

MARK II BUOY

The antenna used in the Mark II buoy was a slightly concave strip of spring steel, similar to that employed in measuring tapes, which maintains itself stiffly straight as it is unreeled. In the assembled buoy this strip was bent over against the side of the buoy and held in this position by a removable cap which also served to house the parachute. This scheme not only assured that the antenna would immediately

erect but also provided a more certain means of removing the parachute safely. In the former design, withdrawal of the parachute was complicated if the buoy was not properly oriented with respect to the static line. Furthermore, removal of the parachute cap decreased the top weight of the buoy in the water, thereby improving stability.

The gravity motor of the Mark II buoy employed stiff paddle blades, hinged to fold within the buoy housing. An alternate design achieved a slight reduction in overall length by arranging for the motor to slide up into the folded assembly when closed. This advantage did not appear to justify the complications introduced.

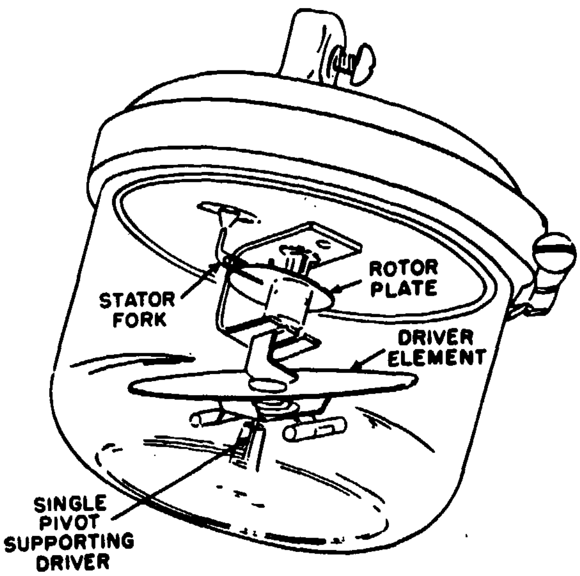


FIGURE 20. Slave-master-type compass capacitor developed for Mark II buoy.

A new and larger compass-capacitor, utilizing the slave-master principle, was designed to insure smoother operation in rough water. A drawing of the unit is shown in Figure 20. The master disk was mounted on a single pivot to permit it to remain horizontal despite tilting of the compass case by as much as 25 degrees. This disk, in turn, magnetically drove the small doubly pivoted slave disk, which was the eccentric plate of the frequency-deviating capacitor.

No formal tests were made of the Mark II buoy but overside tests demonstrated the marked advantage in bearing accuracy offered by the larger slave-master type of compass.

Mark III Buoy

This model was a parallel development of the Mark II buoy and incorporated most of the features and functions of that unit. It differed primarily in the use of the smaller Mark I compass.

Drop tests of this buoy demonstrated the advantages of the separable parachute cap and the simple spring-steel type antenna. However, on listening, there were unwanted noises, attributed to the torque tube and paddle. Furthermore, bearing accuracy was not good in rough water. This unreliable behavior of the compass persisted even after the Mark I compass was replaced by a small one of the slave-master type. The large surface area of the flat-spring antenna caused it to buckle occasionally in the wind. Moreover, the antenna was mounted off center to decrease sharpness of bend when folded, and as a result even a moderate wind interfered with smooth rotation of the buoy.

Mark IV Buoy

The Mark IV buoy was built around the larger more stable slave-master compass of the Mark II unit. The antenna was moved to the center of the top deck, and a rod was substituted for the major portion of the antenna. Three thicknesses of spring-steel tape were used for the bottom section of the antenna to allow it to be bent down against the side of the buoy and at the same time provide greater rigidity.

The keying grooves in the succeeding sections of the telescoping support tube were made with graduated radii so they would nest together more precisely. In addition, small cylindrical sleeves were introduced between adjacent sections so that, when extended, the tube would be more rigid and noise-free.

Numerous drop and overside tests proved the Mark IV design acceptable. On one occasion a submarine at periscope depth was tracked for 2 hours by a PBM plane using two directional buoys. The buoy observations were later checked against the course as shown by the submarine log and against bearings based on visual observations from the plane. These are plotted in

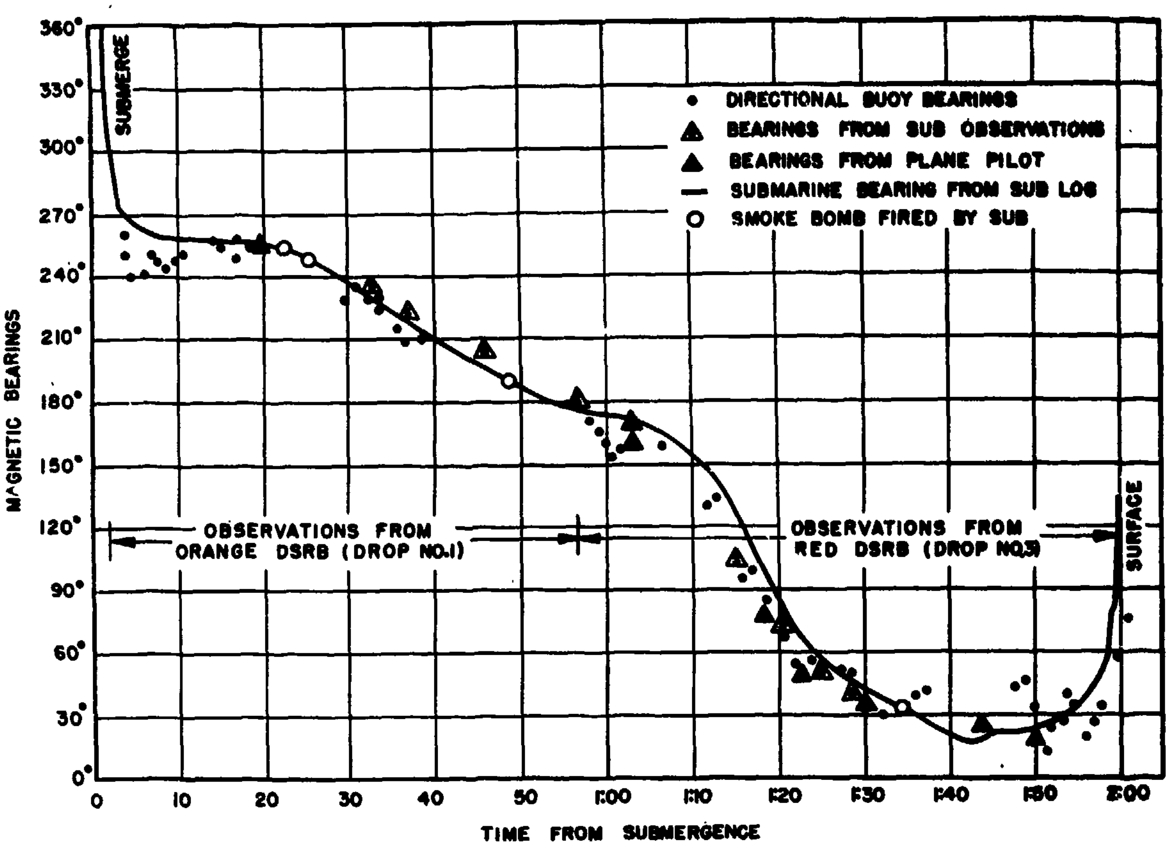


FIGURE 21. Comparison of DRSB bearing indications with other determinations.

Figure 21. It will be noted that the bearing error rarely exceeded 10 degrees.

9.8 THE AN/CRT-4(XN-1) PRODUCTION BUOY

The production buoy is essentially the Mark IV. It is 52½ inches long, 6¼ inches in diameter, and weighs 30 pounds, including batteries. In its closed condition, as shown in the cutaway section of Figure 22, the antenna is folded down along the side of the buoy housing and the hydrophone and motor assemblies are enclosed within the bottom section of the housing. During the launching operation these components automatically extend, the antenna erecting to approximately 40 inches above the top deck of the buoy during the drop and the hydrophone and motor assemblies descending to about 3 feet below the surface of the water after impact. The buoy, with components extended, is shown in Figure 23.

9.8.1 Buoy Housing

The tubular housing is of bakelite-impregnated paper, surmounted by a cap of phenol fabric, and consists of two separate tubes, rigidly attached end to end to provide two distinct compartments. The upper one of these, which contains the radio chassis and batteries, is watertight and constitutes a buoyancy chamber. The lower compartment houses the folded hydrophone and motor mechanism. The top cap provides storage space for the packed parachute and its lines and a seamarker dye packet. In addition it serves, up to the moment of launching, as a cover for the equipment mounted on the top deck of the transmitter section and provides a means for clamping the antenna in its folded position.

The upper section is closed at the bottom by a brass waterseal bulkhead in which is mounted the receptacle of a watertight separable connector for connection to the hydrophone. The aluminum deck at the top supports the

FIGURE 22. AN/CRT-4 (XN-1) buoy, cutaway view.

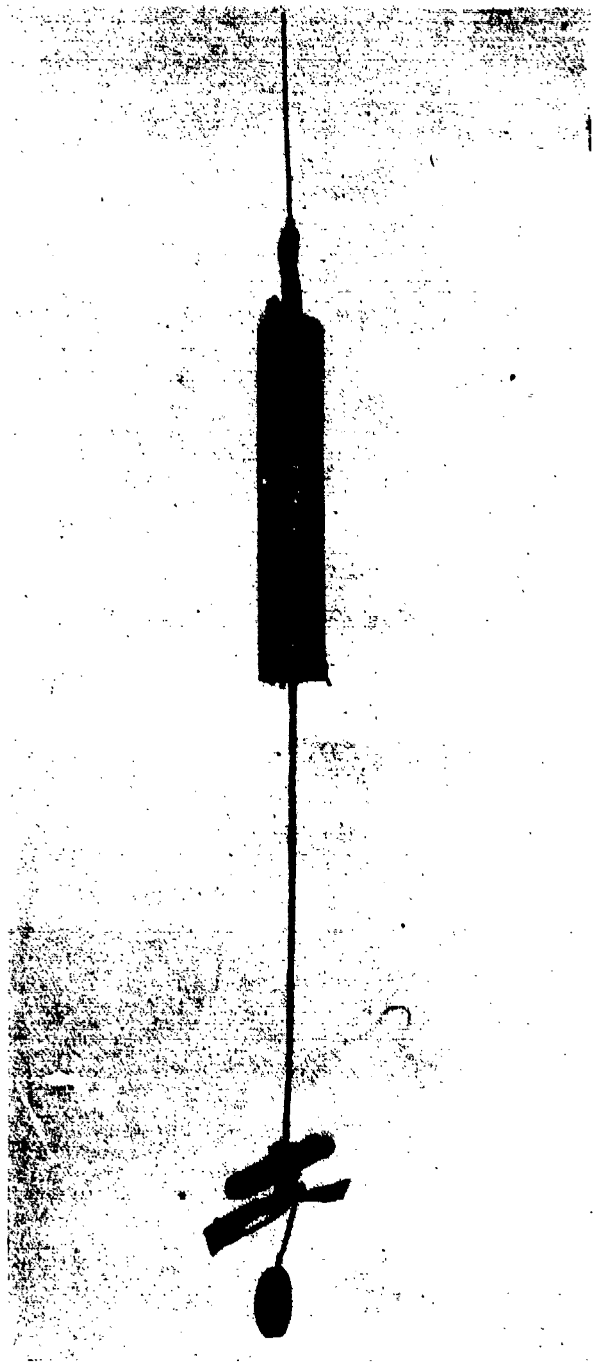


FIGURE 23. AN/CRT-4 (XN-1) buoy with components extended as after launching.

transmitter chassis and the antenna and, with the help of a rubber gasket, completes the watersealing of the buoyancy chamber. To provide electric shielding and thus aid in stabilizing the frequency of the transmitter, the outside of this upper section is sprayed with atomic zinc which is grounded to the transmitter chassis.

The lower section of the housing has a metal bulkhead mounted at the top to support the telescoping tube to which the hydrophone assembly is attached. The bulkhead also provides

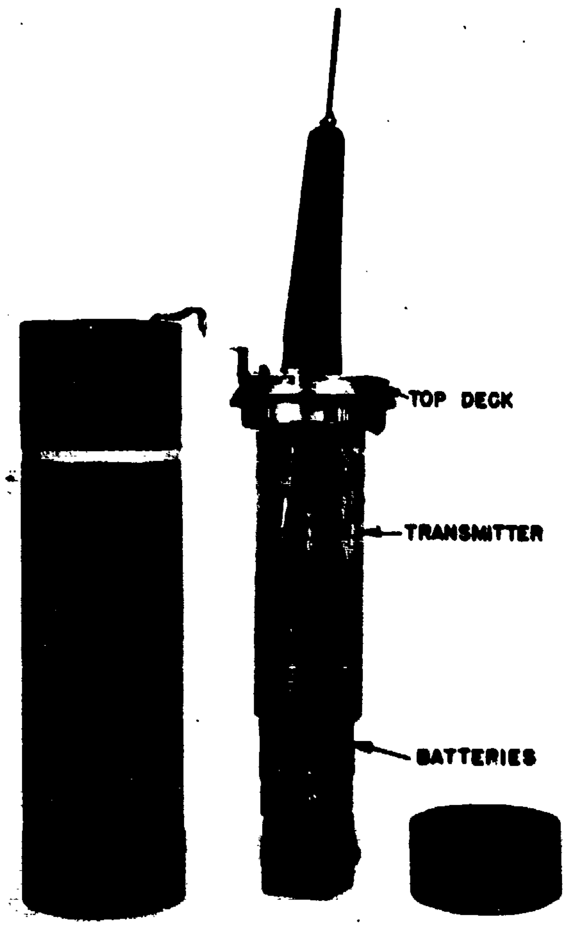


FIGURE 24. Top assembly removed from housing.

accommodation for the coiled hydrophone cable. A nonmagnetic metal band connects the two sections of the housing, and another such band reinforces the bottom edge of the lower section.

Each individual buoy is color-coded to indicate the operating frequency to which its transmitter was tuned at the factory. The painted stripes just below the top of the housing provide this information.

As in the ERSB, for purposes of security a soluble plug of Carbowax, which seals a hole in the top deck, dissolves in a few hours and the buoy sinks after its useful life is ended.

9.8.2 Transmitter Section

Figure 24 shows the top assembly removed from its housing and Figure 25, the top deck in some detail.

ANTENNA

Components of the antenna are shown in Figure 26. The antenna consists of a spring-tempered steel rod 30 inches long attached to a flat stainless-steel spring 9 inches long by 1⅛ inches wide. The spring section is made of three leaves each bowed slightly in the 1⅛ inch dimension. A rubber boot, enclosing the spring section, insures proper insulation and a

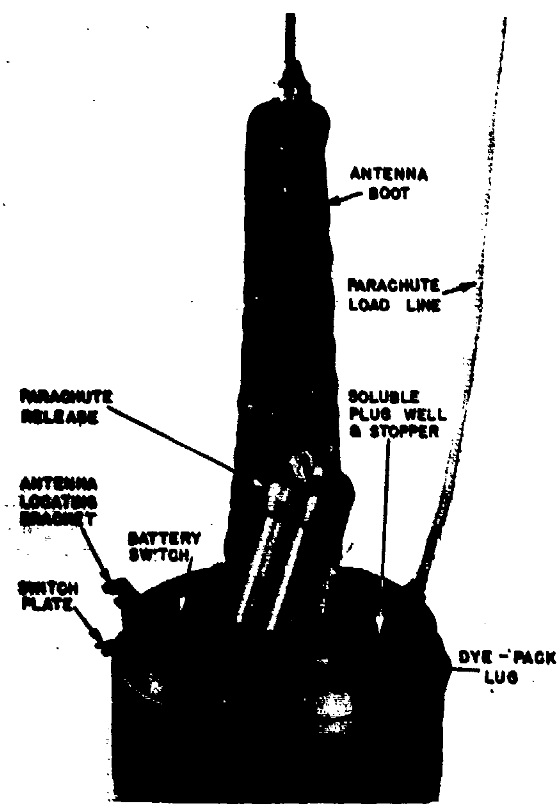


FIGURE 25. Top deck details without dye pack.

cushion of sponge rubber maintains sufficient spacing between antenna and water to minimize capacity variations.

The toggle-type battery switch is spring-actuated, with its on position the normal one. It is held in the off position when the antenna is folded down against the buoy.

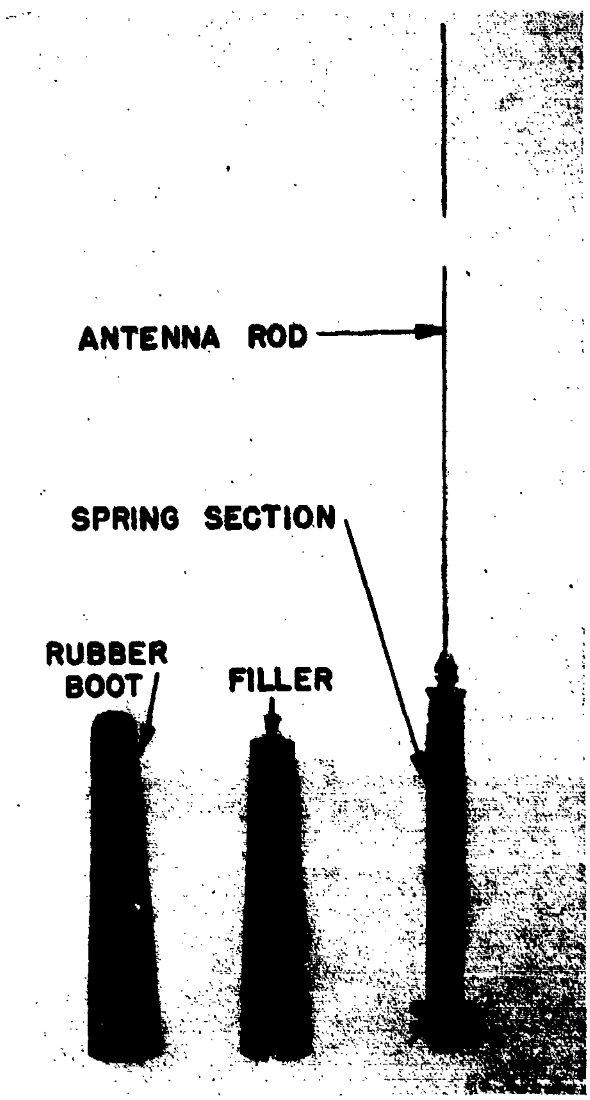


FIGURE 26. Antenna components.

TRANSMITTER CHASSIS

Except for slight modifications, the transmitter chassis is similar to the type used in the nondirectional buoy. Components are mounted on the two sides of a vertical metal plate with the compass at the bottom. This unit is suspended by rubber shock mountings within a nonmagnetic framework and, together with the battery pack, is clamped to the top deck in such a manner as to allow for precise orientation of the compass with respect to the hydrophone at the time of assembly. A transparent acetate tube surrounds the transmitter for protection during adjustment and installation of batteries in the field.

TRANSMITTER CIRCUIT

The circuit of the frequency-modulated transmitter is given in Figure 27. Briefly it consists of a two-stage a-f amplifier followed by a reactance-tube modulator, oscillator, and amplifier. Audio-signal voltages applied to the grid of the reactance tube vary its transconductance and hence the reflected reactance across the oscillator tank circuit. This in turn modulates the oscillator frequency which can be adjusted over the range, 15.5 – 18.0 mc. The plate circuit of the oscillator tube provides frequency doubling, as well as the amplifier tube. The output center-frequency range is thus 62 – 72 mc. This frequency double-doubling arrangement eliminates the necessity for complex neutralizing circuits and also, by quadrupling the frequency deviation due to modulation, provides a 12-db improvement in signal-to-noise ratio.

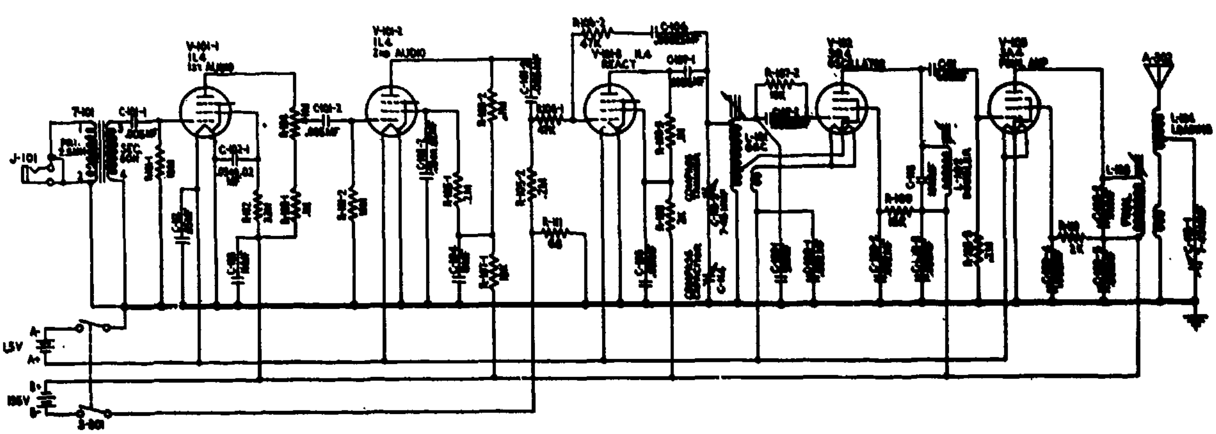


FIGURE 27. Schematic circuit diagram of transmitter.

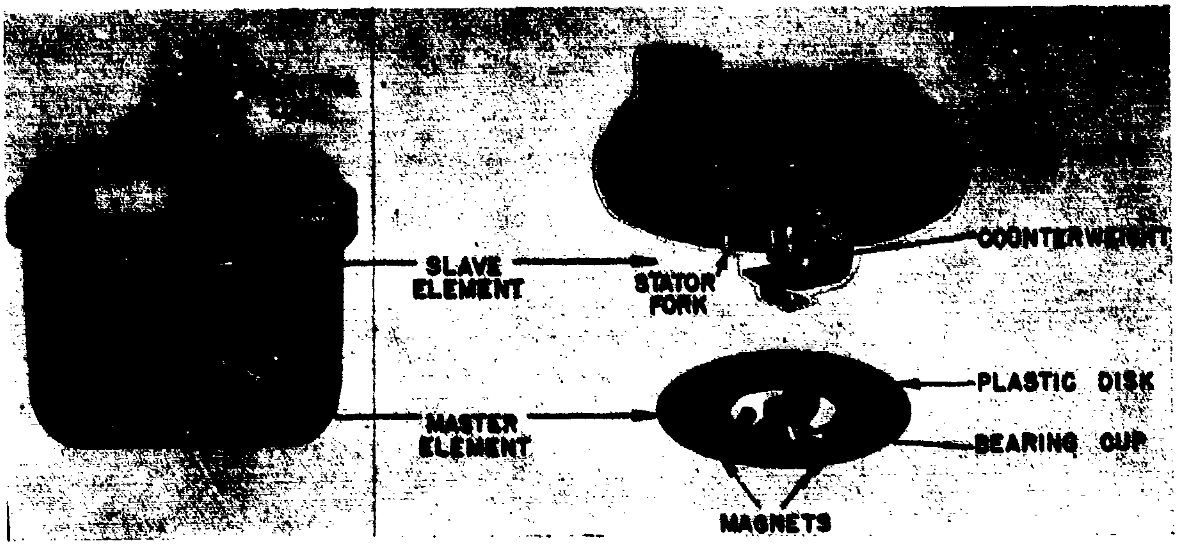


FIGURE 28. Compass-capacitor and components.

ORIENTATION SYSTEM

The compass-capacitor incorporated in the transmitter is of the slave-master type. Details of its construction are shown in Figure 28. Two magnets which act as the driving element are suspended by means of a single-pivot jewel bearing and rotate freely even though the case is tilted up to an angle of 25 degrees. An eccentric metal plate and magnet mounted on a shaft pivoted in jewel bearings at both ends comprise the slave element. The eccentricity of the plate is such that as it rotates the capacity between it and the stator fork which straddles it varies continuously over the range 2.5 to 2.8 μf. This capacity is connected as part of the oscillator tank circuit. The 0.3-μf variation provides a frequency swing of ± 75 kc in synchronism with buoy rotation.

9.2.3 Bottom Section

HYDROPHONE SUPPORT

The telescoping torque tube for supporting the hydrophone and motor assembly is shown in Figure 29 and in sectional drawing in Figure 30. It consists of seven sections of brass tubing of graduated diameters and measures about 12 inches long when collapsed and 68.5 inches extended. Thin spring sleeves in the form of open bands ride between the tubes and

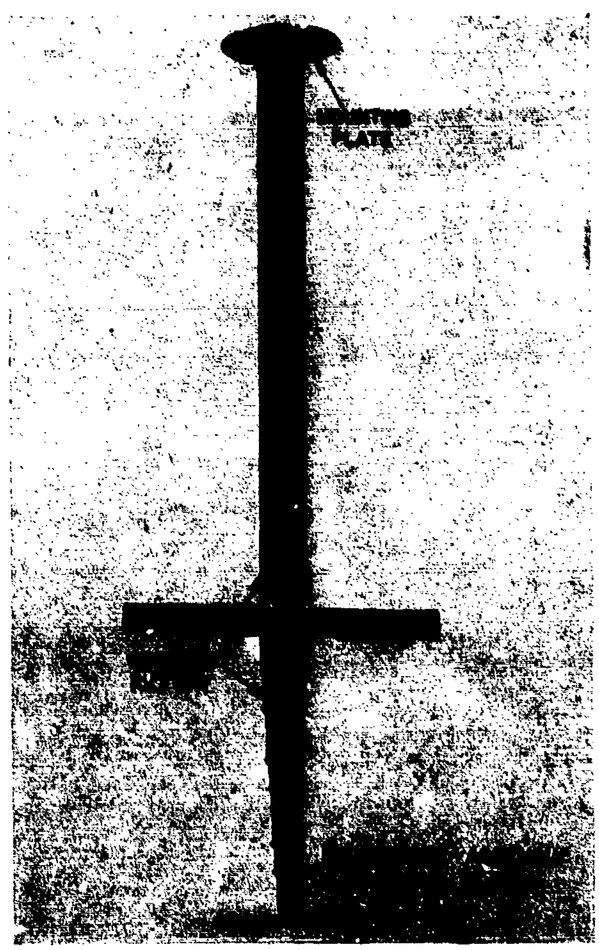


FIGURE 29. Telescoping support tube.

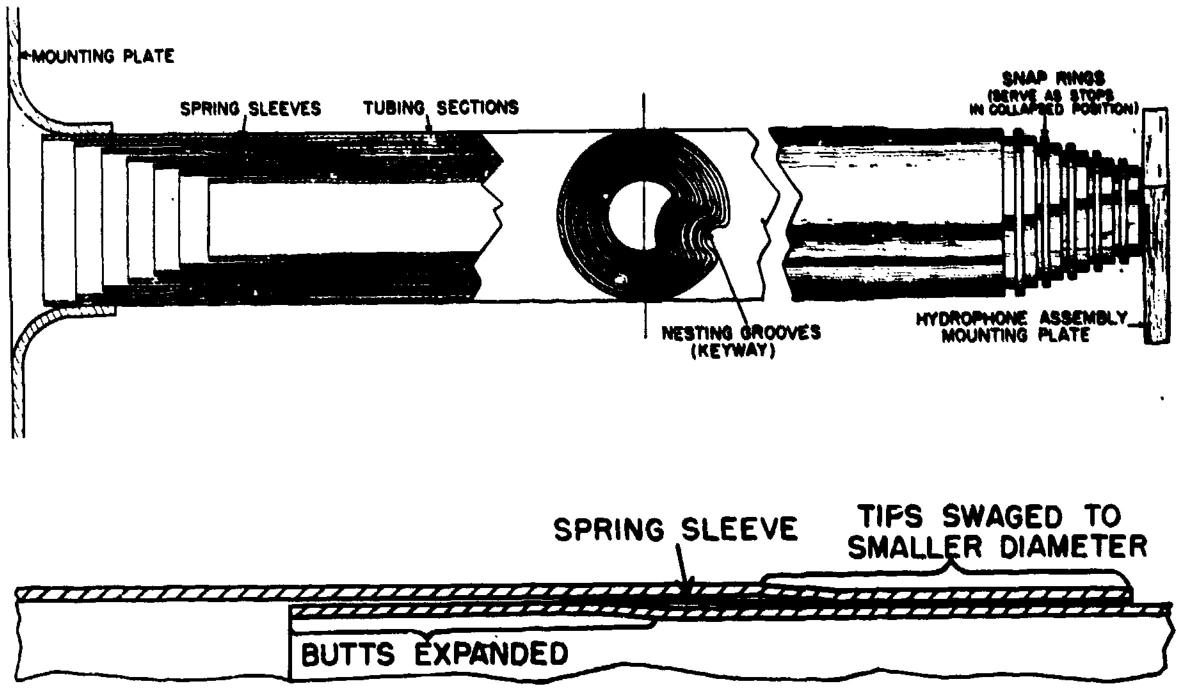


FIGURE 30. Sectional drawing of telescoping support tube.

provide a wedge between adjacent tubes when the system is fully extended. These lock the sections securely into position, increasing stiffness and minimizing undesirable noise.

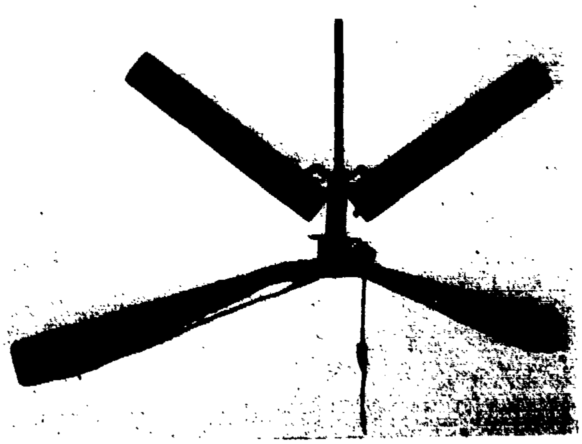


FIGURE 31. Bottom assembly with hydrophone partly unfolded.

HYDROPHONE

Attached to the lower end of the torque tube is the hydrophone and motor assembly. Figure 31 shows the hinged halves of the hydrophone falling into operating position, to be held in horizontal line by a spring hook. The motor blades, aided by spring hinges, have already assumed their operation positions.

Each section of the hydrophone consists of a 12-inch length of annealed seamless nickel tubing, $1\frac{3}{4}$ inches in diameter and 0.025-inch in wall thickness, on which 83 turns of Vinylite-

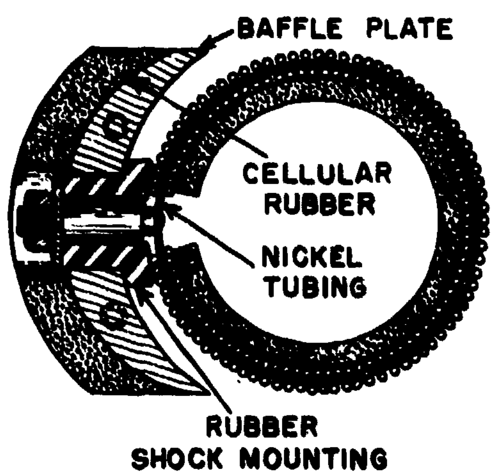


FIGURE 32. Cross section of hydrophone.

insulated wire are wound toroidally. The tube is then lined with a thin layer of cellular rubber, backed with an aluminum baffle plate, and magnetized by discharging a large capacitor through the toroidal winding. A cross-sectional drawing of this structure is shown in Figure 32.

The rubber lining and baffle plate provide improved directional properties of the hydrophone in both the horizontal and vertical planes. Its pattern described in Chapter 6, Volume 11, Division 6, in the horizontal plane is shown in Figure 33. To gain the full directional effectiveness of the hydrophone, it is essential that the two sections be as nearly identical as possible. The two nickel tubes are therefore

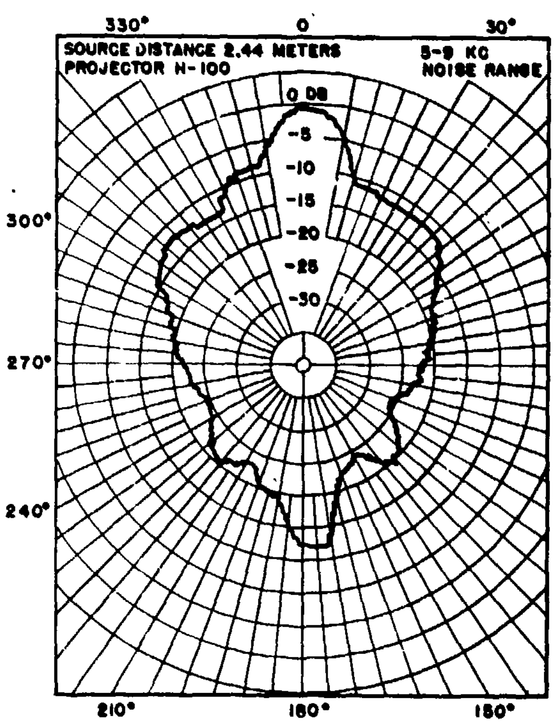


FIGURE 33. Hydrophone response pattern.

adjacent sections from the original tubing stock, are heat-treated in the same manner, and are assembled in their original relative positions in the final hydrophone.

MOTOR ASSEMBLY

A close-up of the motor assembly, Figure 34, shows the reel and line, line guides, paddle, and motor weight. The bottom plate of the buoy when detached serves as the weight, causing the nylon line to unwind and rotate the reel and hydrophone at about 4 rpm. The relatively large blade surface of the paddles provides the necessary back pressure.

Because of the close mechanical and acoustic coupling between the motor and the amplifier and because of the large voltage gain of the amplifier (about 100 db), it is extremely important that the total noise from the drive mechanism be as low as possible. So critical is this that ball bearings could not be used in the reel, and a special sleeve bearing is provided. Other factors which contribute toward quiet operation include composition rollers in the line guide, a positive latch for locking the two sections of the hydrophone in line, strong springs in the paddle hinges, shock-mounting of the hydrophone baffles, and the special joint construction of the torque tube described above.

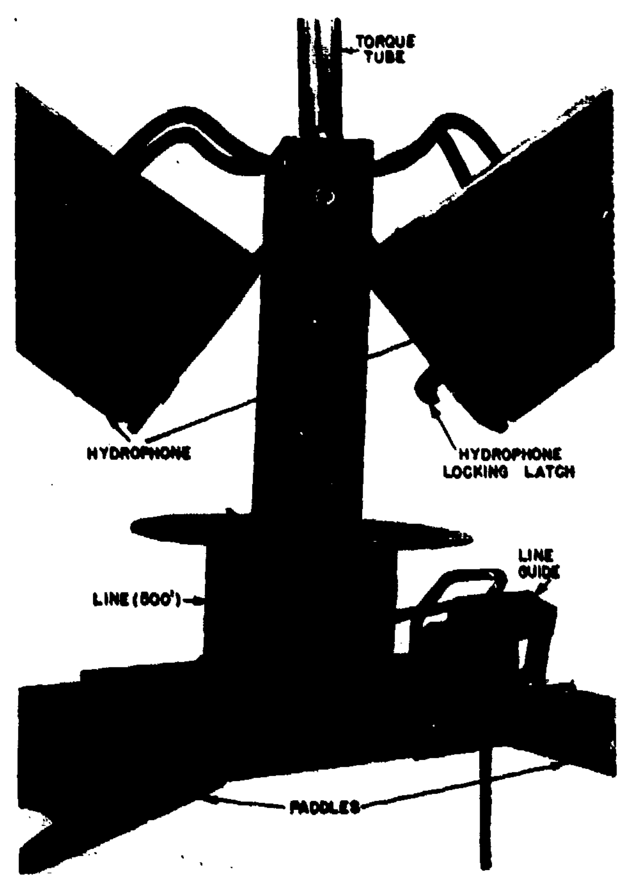


FIGURE 34. Motor assembly and hydrophone lock.

Besides serving as the motor weight during operation, the base plate is the protecting closure for the bottom of the buoy. It consists of two parts, a perforated outer safety plate and the inner release disk held together by spring hooks. Release springs attached to the buoy housing hold the inner disk in position, as shown in Figure 35. On impact with the water this disk is forced upwards, the release springs unhook, and the hydrophone and motor assemblies fall into operating position.

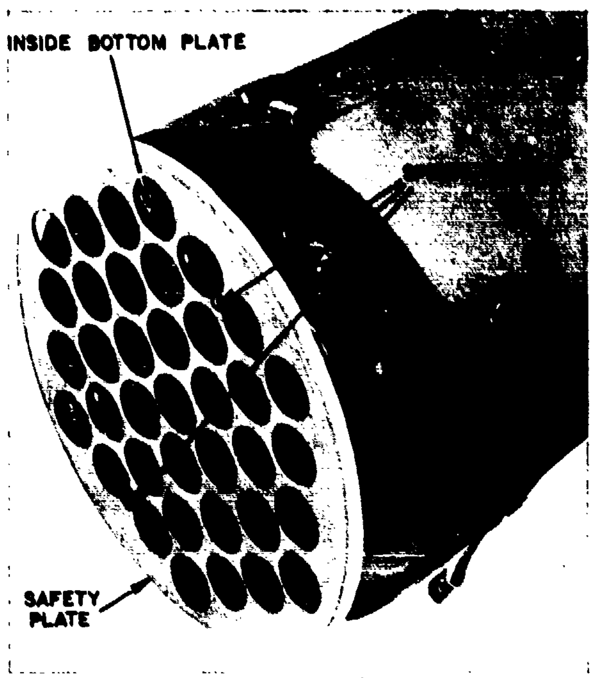


FIGURE 35. Bottom plate at instant of automatic release.

A special bottom plate which can be triggered by hand is provided for launching from surface craft.

9.8.4 Cap Section

The molded phenol fabric top cap of the buoy houses the antenna components and dye pack and serves to hold the antenna in its folded position. At the bottom edge of the nose of the cap is a hinged flap which holds the antenna against the side of the buoy and thereby keeps the battery switch in its *off* position. Releasing this flap permits preflight testing of the buoy.

On launching, one end of a static line is attached to the aircraft, the other to the static tape which passes through the top of the cap to a key. The key in turn is connected to the top of the parachute. As the cap is pulled off and the parachute emerges, the key turns and static line slides out, thereby freeing the parachute and casting off the cap. The antenna also erects during this operation, thus turning on the transmitter.

PARACHUTE

The parachute is of nylon, 36 inches in diameter, with twelve 6-foot rayon shrouds terminating in a 15-foot load line. The other end of the load line is attached to the top deck of the buoy through a hydraulic-delay release which serves to cast off the parachute on impact with the water.

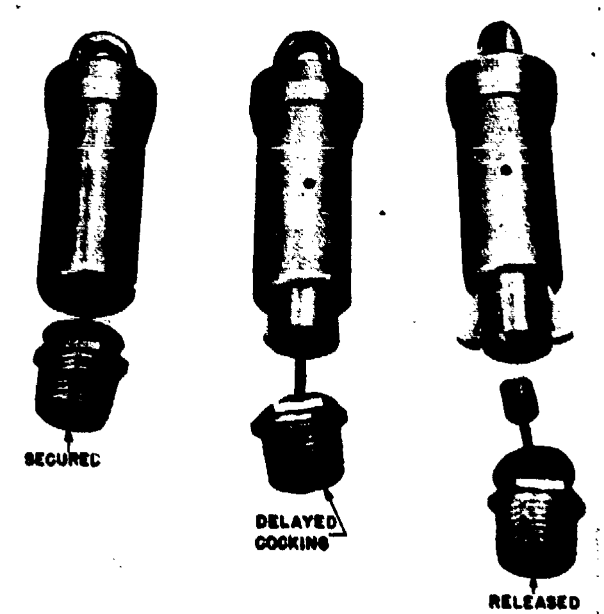


FIGURE 36. Stages in operation of parachute release.

Three stages in the operation of the parachute delay mechanism are shown in Figure 36. As the parachute blossoms the plunger is pulled downwards, but the hydraulic delay is such that about 3 seconds are required for it to reach its extreme position. During this time the side hooks are held locked under the cable button by the confining action of the barrel wall.

This delay allows for the first few moments of erratic motion following parachute opening after which the pull becomes steady. When the buoy reaches the water, the pull is removed, the side hooks spring out, and the parachute and release mechanism are discarded.

Dye Pack

The dye pack, consisting of standard life-jacket fluorescein powder enclosed in a cotton bag, is sealed in a Vinylite-impregnated bag which is tied to the top of the buoy. One side of the bag is unsealed during launching, and thus coloring of the water starts as soon as the buoy strikes the water and assists in locating the buoy visually from the air. Figure 17 shows the position of the bag in the water and the discoloration produced. Active life of the dye pack in water is from 1 hour to 6 hours, depending on water conditions.

9.9 THE AN/ARR-16 RECEIVER

The AN/ARR-16 receiver used with the DRSB is a modification of the AN/ARR-3A receiver employed with the nondirectional buoy. This modification involves principally the addition of a vacuum-tube voltmeter circuit as the direction-indicating component.

Figure 37 shows the receiver and its accessories. These include the 24-volt power supply, and two remote bearing-indicating meters and phones, one for use at any point in the plane, the other for the operator. Provision is also made for plugging the plane's interphone system into the receiver to enable the operator to receive information and commands while listening for buoy signals.

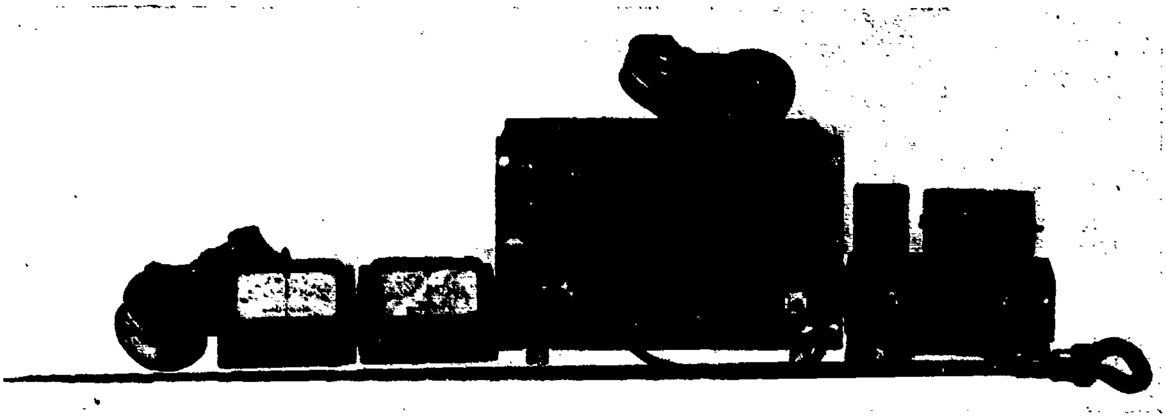


Figure 37. The AN/ARR-16 directional buoy receiver and accessories.

Receiver Circuit

The receiver employs 14 tubes in the circuit of Figure 38, and tunes over the frequency range from 62.3 to 72.3 mc. Operation of the bearing-indicating component will be described here. Other technical and operational details are available elsewhere in this chapter and in references 2 and 3.

In the operation of the receiver, the a-f output voltage of the discriminator tube is applied to the a-f amplifier stages, while any slower variation of voltage due to carrier center-frequency shift is segregated and applied to the input of the AFC system. As the carrier is caused to shift continuously by the rotation of the buoy, the AFC system receives a constantly varying voltage which is measured by the vacuum-tube voltmeter circuit. The scale of the indicating meter is calibrated in points of the compass instead of in volts and thus provides a direct indication of the orientation of the buoy to which it is tuned. The face of this meter is shown in Figure 39.

For accurate bearing readings it is necessary to tune the receiver to the precise center frequency of the carrier and to regulate the voltage applied to the vacuum-tube voltmeter circuit (by the *scale expander* potentiometer) to such a value that the indicating meter just

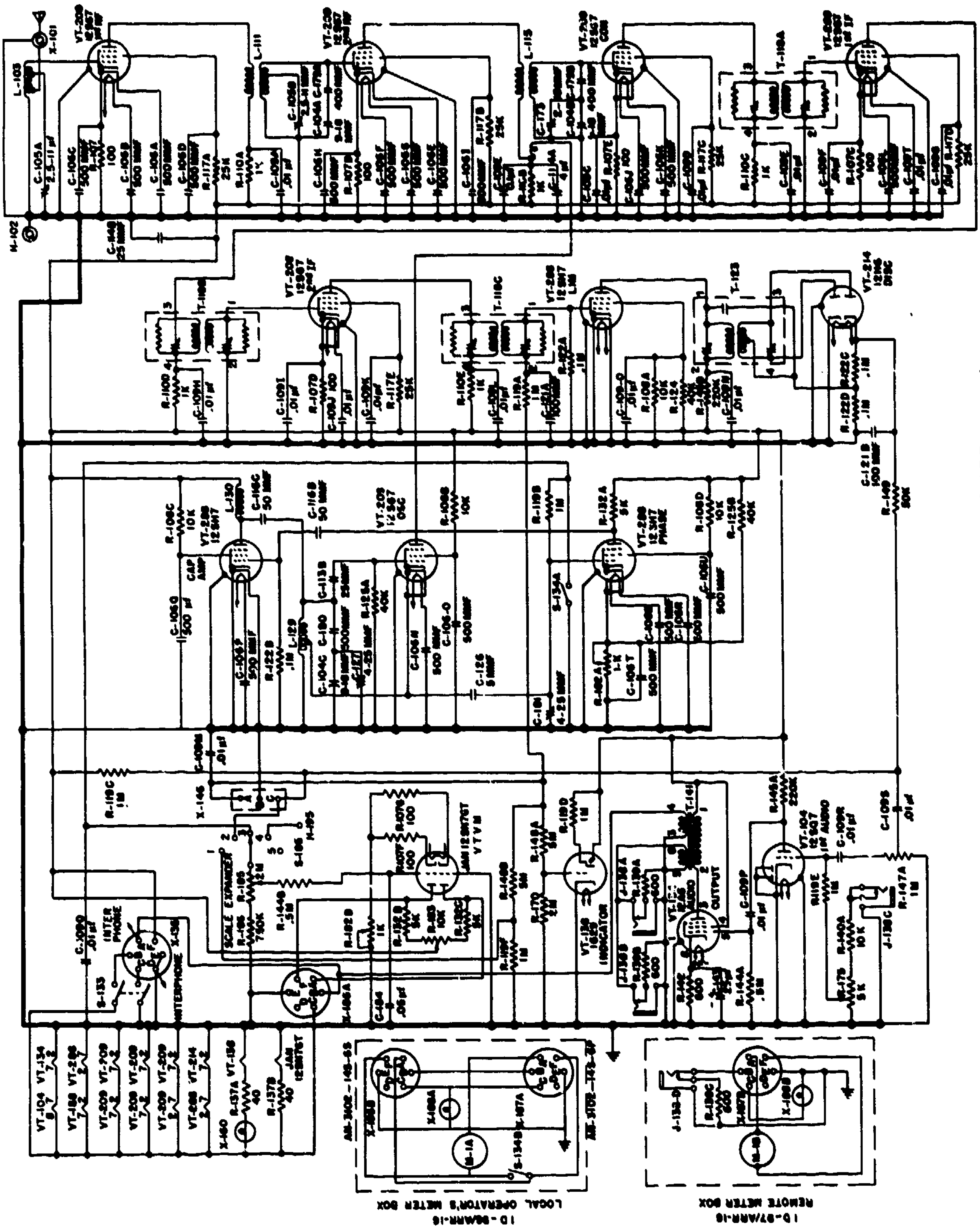


FIGURE 38. Schematic circuit diagram of AN/ARR-16 receiver.

covers the entire scale. Proper orientation of the compass with respect to the hydrophone is of course necessary. This is checked at the time of assembly with due allowance for the drag which the rotating liquid exerts on the elements of the compass as the unit revolves.

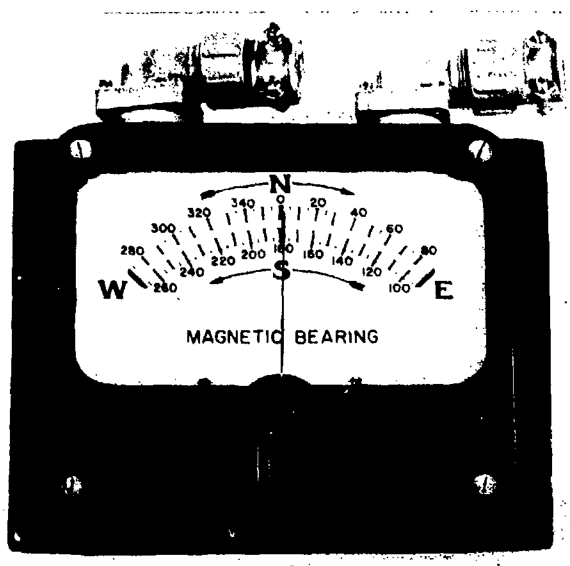


FIGURE 39. Meter face of bearing-indicator.

9.10 OPERATION OF THE EQUIPMENT

The following is a brief description of launching procedure and the sequence of automatic operations that then occur.

The buoy may be manually launched through a hatch or mechanically launched from the bomb bay. In either case, the static line (attached to the plane) is connected to the static tape in the cap of the buoy. As the falling buoy reaches the limit of the static line, the cap is pulled off, the antenna erects, the battery switch is released to turn on the transmitter, and the dye pack and parachute are pulled from the cap. This releases the static line and the now useless cap is discarded. The parachute then blossoms, the parachute release is cocked, and the unit is eased downwards toward the water. On striking the water the bottom plate is automatically unlatched and the parachute is released. The bottom assembly then drops out of its housing, extending and locking the torque tube. The hydrophone and motor paddles assume operating positions and the bottom plate, serving as motor weight, starts the buoy rotating.

The effective operating life of the buoy depends on water depth, on the amount of line wound on the motor reel, and on the battery supply. The motor reel is wound with about 500 feet of line which is expended at about 100 feet per hour. In deep water it therefore rotates for about 5 hours, which is also the life of the battery pack under best conditions. If the batteries are aged, or if ambient temperature is low, their life may be as low as 2 hours.

Before a buoy is launched, its carrier frequency is ascertained from its identifying color band, and the receiver may be set to this frequency at once. When the buoy reaches the water it immediately starts to relay underwater sounds, and if any submarine is within sound range, its bearing from the buoy can be determined. To locate the submarine more precisely, triangulation can be employed by dropping a second buoy transmitting at a different frequency.

9.11 PERFORMANCE TESTS

On completion of the first hundred production buoys, the Navy arranged to make comprehensive tests to determine their operating characteristics. Tests were made over an extended period of time and under various conditions of the sea. Besides the necessary surface craft, eight aircraft and five submarines (two of them Italian) participated in the program.

SUBMARINE TARGETS

A summary of the results on location of submarines is given in the graphs of Figures 40 and 41. Although all submarines employed as targets were in excellent condition and definitely quiet in operation, it was necessary to discard a large number of observations because of noise which developed in some of the submarines during the tests. Maximum buoy ranges resulting from shaft squeals or other unusual sounds are therefore not included in the summary.

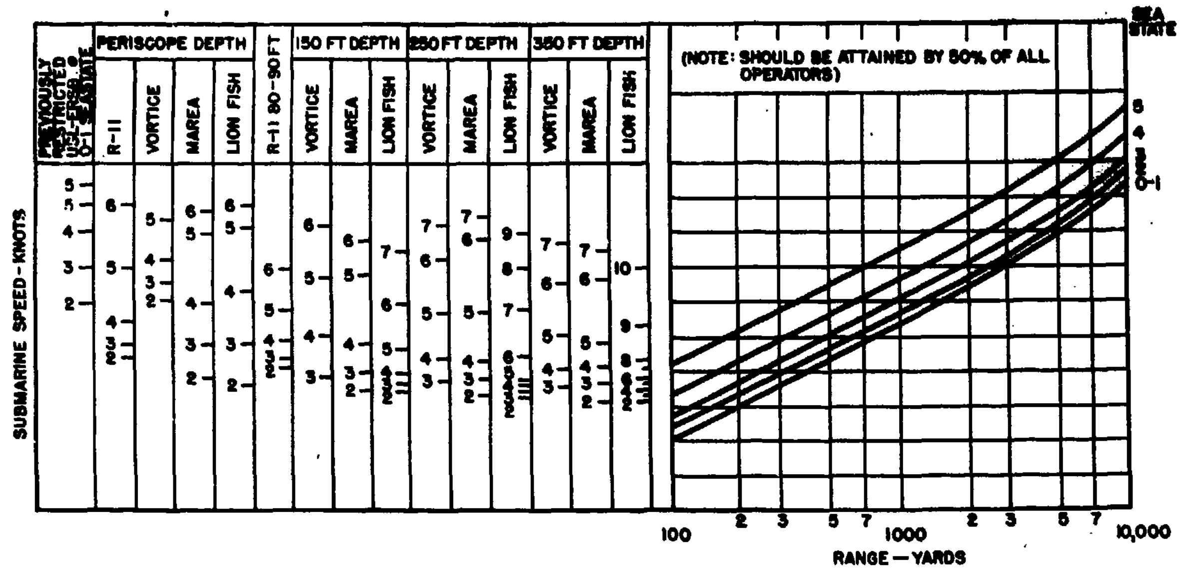


FIGURE 40. DRSB maximum detection ranges for submarines.

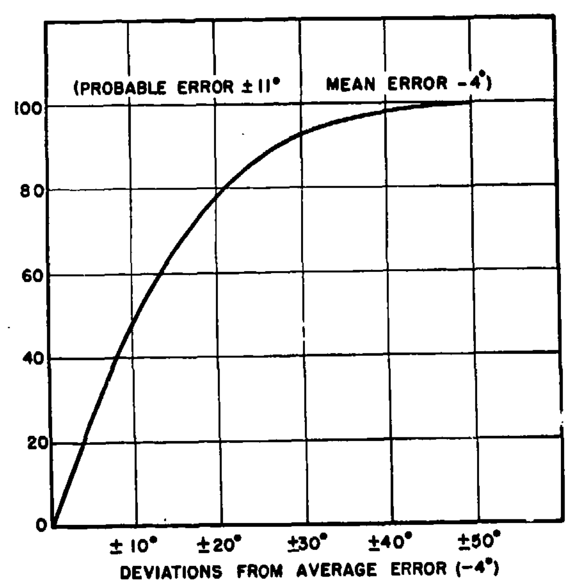


FIGURE 41. Bearing accuracy of DRSB.

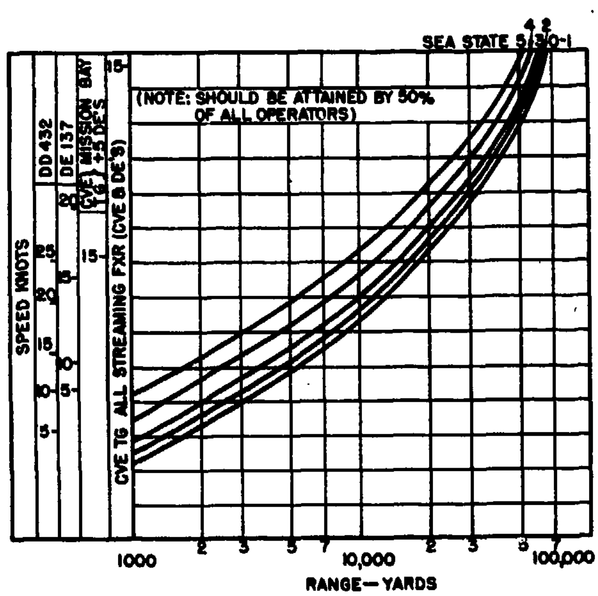


FIGURE 42. DRSB maximum detection ranges for surface craft.

The average maximum range at which various submarines could be detected with the DRSB is given in Figure 40 for various states of the sea and for different submarine speeds. To ascertain this range from the graph, follow a horizontal line from the number on the left corresponding to the speed of the submarine concerned over to the point where it intersects the line representing the state of the sea and read the position of this point on the range scale. For instance, the Lion Fish, at 10 knots, could be picked up at 3,000 yards in a quiet sea and at about 700 yards in a state 5 sea.

The graph of Figure 41 indicates that the average observer attains an accuracy of about ±10 degrees in bearing determination.

At the frequency used by the DRSB, radio range approximates line-of-sight and therefore depends on the elevation of the aircraft. Actual ranges determined were: 6 miles at 200 feet

elevation; 11 miles at 500 feet; 16 miles at 1,000 feet; and 26 miles at 3,600 feet.

Surface Craft Targets

Figure 42 presents a summary of data on the effective sonic range of the DRSB against various antisubmarine warfare [ASW] craft, both as a function of target speed and state of the sea. This figure is read in the same manner as Figure 40.

DRSB from Surface Craft

Use of the nondirectional ERSB by surface craft requires that the ship remain quiet or move very slowly. Because of the directional characteristics of DRSB, it was found that a surface ship could move in toward a buoy or target and still not produce too much interference if it laid its course to avoid a buoy-ship bearing within about 30 degrees of the buoy target bearing. This suggests the possibility of closer cooperation between the air and surface components of a composite ASW task group than is possible with the nondirectional ERSB.

The radio range of the buoy to a receiver aboard a surface ship was found to be limited to about 5 miles because of the relatively small elevation of the buoy antenna.

As a result of the above tests, the adoption of the DRSB was recommended and an original procurement of 1,000 units was increased to 7,000.

Chapter 10

SUBMARINE LISTENING EQUIPMENT—JP AND JT SYSTEMS

10.1 INTRODUCTION

Early in the submarine listening program, the use of existing sonic equipment had been abandoned as ineffective because of the limited frequency response and poor directionality of available hydrophones, the high submarine self-noise levels in the sonic frequency range, and the lack of adequate control of amplifier frequency response characteristics. At the time of our entry in World War II, U. S. submarines were capable of listening in the supersonic range only. The equipment was capable of providing accurate bearings and detecting, at a considerable range, noise produced by propellers turning at above cavitation speeds. However, the characteristic noise peaks which make it possible for an experienced sound operator to identify different types of vessels at long range are largely in the sonic frequency band. In addition the noise produced by stationary or slowly moving vessels is generally of machinery origin with few, if any, components in the supersonic region. Further, as sonic frequencies are subject to less attenuation in sea water, they can be detected at greater maximum ranges. A sonic system was therefore desirable for early detection and identification of the target. In addition, the supersonic transducers on most fleet-type submarines are mounted near the keel, where it is impossible to lower the head for listening if the boat is lying on the bottom. Under this condition, a submarine equipped with only supersonic gear is without acoustic means for obtaining information about surface vessels in the vicinity. For this reason, both JP and JT gear provide topside mounting of the hydrophone.

Work on topside submarine equipment progressed with these ends in mind, to identify types of ships and to detect sounds produced by stationary or slowly moving surface craft, along with the additional aim of indicating any detectable noise produced by the submarine itself. Research made possible the development of toroidal and straight magnetostriction hydrophones of rugged and simple construction possessing good wide-band frequency response characteristics together with good directionality.[1,2] Preliminary tests showed that listening with these hydrophones was possible at speeds of from 3 knots to 6 knots. They also indicated that, if the hydrophone could be made directional, an effective sonic listening system for submarines was feasible.

Development work was consequently undertaken and proceeded in parallel with the development of the directive sonic listening equipment for small patrol craft discussed in Chapters 4 through 7. This work led first to the design and construction of the JP-1, JP-2, and JP-3 sound receiving equipment for submarines and later to the development of the JT sonar equipment.

The factors controlling the listening range of such equipment are highly variable. Under very favorable conditions, surface ship propeller sounds have been heard with the JP hydrophone at ranges in excess of 20,000 yards and the auxiliary machinery of destroyers detected up to approximately 1,000 yards. However, it is believed that the effectiveness of the JP equipment is reduced by the structural transmission of vibration from the submarine to the hydrophone through the training shaft, by waterborne noise from the propulsion machinery, auxiliaries, and superstructure of the submarine, and by the considerable effort necessary to train the hydrophone by hand for extended periods of time.

As tactical information concerning the sonar needs of the submarine forces became available through reports of patrol activities, plans were considered for improving either the existing JP or the WCA gear in use. Although both modification plans presented were judged to be equally desirable from a tactical standpoint, it was believed that changes made primarily to

the JP system would result in faster production and less installation-time requirement. Improvements include the use of a split delobed hydrophone and *right-left indicator* [RLI] system to permit more accurate determination of bearings and incorporation of a supersonic converter to allow sonic or supersonic tracking of targets. Continuous rotation and power-training of the hydrophone, a two-way talk-back system, and various other new features combined to reduce operator fatigue and to attain closer coordination between the sound operator and the attack team.

FIGURE 1. JP-1 hydrophone installation.

JP-1, JP-2, aad JP-3 Equipment

The JP-1, JP-2, and JP-3 equipment[a] *is designed to be used on submarines to detect surface ship sounds and give their relative bearing from the submarine and to monitor submarine self-noise. It comprises a 3-foot magnetostriction wood-core line hydrophone and baffle, a sonic listening amplifier, and a hand-training mechanism which can be used with the submarine underway at 3 to 4 knots submerged. To permit operation while the submarine is on the ocean bottom, the hydrophone is mounted topside on a shaft which extends through the forward torpedo room pressure hull. With its associated baffle, the hydrophone is directional in the horizontal plane and its response rises with frequency at the rate of approximately 6 db per octave from a value of about –115 db vs 1 volt per dyne per sq cm at 1,000 c. The amplifier is equipped with various high-pass filters to aid in discriminating against ambient and self-noise and to increase the directivity for accurate bearings. Possible bearing accuracy on certain types of noise sources is within approximately 1 degree. Surface ship propeller noise can be heard at ranges out to 20,000 yards under good weather conditions and destroyer auxiliaries out to 1,000 yards. This equipment was developed by CUDWR-NLL.*

10.2 GENERAL DESIGN CONSIDERATIONS

For a submarine's sonic listening system to be most useful, a number of specific requirements must be met.

1. Its listening range for propeller sounds should be several thousand yards and auxiliary machinery noise should be detectable at a range of several hundred yards under good conditions.
2. It should have sufficient directivity to discriminate against the noise from the submarine's own propellers at low speeds and to locate target bearings with reasonable accuracy.
3. Its hydrophone and amplifier should have good response characteristics in the lower frequency range (down to about 100 c) to detect the components in this region from surface craft auxiliary machinery.
4. The amplifier should be provided with high-pass filters to aid in the accurate determination of bearings and to discriminate against the noises of the submarine's own machinery when necessary.

[a] JP-2 and JP-3 sound receiving equipment are subsequent models of the JP-1 and embody only relatively minor changes. The term JP is used informally in the text to refer to any or all of the models. This equipment should not be confused with the JP overside and through-the-hull equipment for small patrol craft discussed in Chapter 7.

5. Its dimensions should be minimal because of the space limitations on all submarines.

6. In so far as feasible its components should operate directly from the ship's d-c power supply to facilitate use during evasive maneuvers.

10.3 EARLY MODELS

In the first model of the topside-mounted sonic listening equipment, the toroidal magnetostriction hydrophone was fitted with a ring-shaped iron baffle backed with a cork and rubber compound to provide front-to-back discrimination. The amplifier, adapted from small patrol craft listening equipment, was modified to provide for attenuation of the higher frequencies and to permit a diode rectifier to be used in the listening channel when desired. The amplifier loss at higher frequencies gave the system an overall frequency response that was essentially flat over the sonic region. The diode rectifier arrangement, used in conjunction with a 5,500-c high-pass filter available in the amplifier, was found to aid the operator in taking propeller turn counts and also to give improved bearing accuracy under some conditions. Power for the amplifier was supplied by a special set of A and B batteries furnished with the equipment.

Six units of this model were installed on R-class submarines, utilizing the training shaft of the topside-mounted JK supersonic gear with which these boats are equipped. Extensive tests, designed to evaluate the characteristics of the sonic equipment and to compare its performance with that of the JK supersonic gear, were conducted in deep water off Key West and in the comparatively shallow water of Long Island Sound with the following results.

1. No essential differences were detected in the performance of the sonic gear in deep and shallow water areas.

2. Sounds from surface ship auxiliary equipment were observed and frequently identified by sonic listening at distances up to several hundred yards under average listening conditions.

3. Propeller sounds were generally detected at greater distances with the sonic than with the supersonic equipment.

4. The capabilities of the sonic and supersonic systems to determine the bearing of a target were essentially equal.

5. The ability to identify signals and to take propeller turn counts on the sonic equipment was equal or superior to that on the supersonic gear.

6. At submarine speeds in excess of 8 knots, interference from the submarine's own screws was found to be slightly greater on the sonic than on the supersonic system.

7. The sonic equipment was found to have slightly less front-to-back discrimination than the JK equipment but had no ambiguity of direction.

A second model was constructed for tactical use on P-class submarines (also having topside-mounted JK gear) and for test installations on two new-construction boats. This model utilized substantially the same hydrophone as the earlier units but was provided with an improved amplifier having considerably more gain at frequencies below 500 c and powered from the ship's batteries using a line filter to suppress transients.

The new-construction submarines, having no topside-mounted JK gear, required the provision of separate training mechanisms for the sonic gear. Some difficulty, due to binding of the shaft at deep submergence and to noise caused by tight packing glands, was encountered with these mechanisms.

10.4 PRODUCTION MODEL JP-1 EQUIPMENT

Patrol reports from submarines equipped with topside-mounted sonic listening equipment confirmed the tactical effectiveness of this type of gear. Continued development work resulted in the design and construction of a new model, designated the JP-1 sound receiving equipment, intended primarily for installation on new-construction submarines. The JP-1 equipment utilizes a straight magnetostriction hydrophone in place of the former toroidal unit and incorporates a number of other improvements over the earlier models.

Hydrophone and Baffle

The straight magnetostriction hydrophone used with the JP-1 equipment is of wood-core construction, 3 feet long, and is mounted 30 inches above the submarine's deck. The unit is equipped with an acoustic baffle consisting of a hollow, free-flooding bronze casting covered on the back by a blanket of air-filled, noncommunicating-cell neoprene.

The hydrophone has a front-side open-circuit sensitivity of approximately −115 db vs 1 volt per dyne per sq cm at 1,000 c. Its response rises with frequency at the average rate of about 6 db per octave in the region between 200 and 10,000 c. The baffle provides a front-to-back discrimination which varies from about 5 to 15 db in the range of 500 to 10,000 c.

Mounting and Training Mechanism

The hydrophone mounting and training mechanism, designed and manufactured by the Navy, varies somewhat in detail, according to the class of submarine for which it is intended. It consists essentially of a handwheel geared to a watertight hollow vertical shaft on which is mounted a simple azimuth indicator. The hydrophone cable enters the pressure hull through the shaft.

Amplifier

The amplifier, installed near the after bulkhead of the forward torpedo room, is designed to operate from a d-c power supply of 120 volts. It is of the resistance-coupled type, employing negative feedback between the first two and the last two stages with a push-pull output stage to provide ample power for listening at the low frequencies. An output transformer with a nominal impedance of 300 ohms provides for low-impedance headphone or loudspeaker monitoring; a high-impedance output is provided for crystal headphones. The voltage for the tube heaters, which are connected in series, is controlled by a voltage regulator tube which permits operation on line voltages varying from 85 to 130 volts. A set of filters is provided between the second and third stages for controlling the frequency characteristics of the amplifier. By means of these filters the low frequencies may be emphasized or suppressed as necessary to reduce unwanted noise and improve the operator's ability to hear the desired signal.

Visual detection based on the higher frequency components of received signals is provided by an electron ray (magic-eye) tube in the amplifier. By switching in a diode rectifier, the operator may introduce harmonic distortion into the listening circuit. The distortion produced in this way frequently improves the distinctness of propeller turn counts.

Associated with the amplifier is a circuit for magnetizing the hydrophone. This circuit consists of a bank of condensers, charged by the main power supply voltage and discharged through the hydrophone coil by means of a key switch.

A filter consisting of r-f and a-f sections in tandem is provided for the power supply. Both circulating and longitudinal noise currents are suppressed in the battery supply line. A typical JP-1 forward torpedo room installation is shown in Figure 2.

Figure 2. JP-1 installation in forward torpedo room.

10.5 PERFORMANCE

Tests and patrol reports indicate that the inherent noise and sensitivity of the JP-1 system are such that the detection ranges obtained are limited principally by self and ambient noise or thermal gradient conditions of the water. Where thermal gradients are the con-

trolling factor, the ranges obtained with sonic and supersonic equipment on propeller sounds are about equal. In the absence of controlling gradients, the JP-1 equipment usually gives somewhat greater ranges than the supersonic gear.

Noise

At speeds below about 5 knots, listening is not seriously affected by noise from turbulence around the JP-1 hydrophone or by noise from the submarine's propellers except when the boat is accelerating rapidly. Of greater significance is noise from power operation of the bow planes, stern planes, and steering and from certain rotating equipment within the submarine. Some of the noise from internal sources is structurally transmitted to the hydrophone through the training shaft.

Bearing

The directionality of the system enables an experienced operator to determine bearings within approximately ±1 degree on a source, such as cavitation noise, having considerable energy in the higher frequency region.

Hydrophone

The hydrophone and baffle are sufficiently rugged to stand up under ordinary service conditions. They have been tested at hydrostatic pressures of over 450 psi without observable effect and have been subjected to underwater explosions of depth charges at close range. In one instance such an explosion somewhat flattened the hydrophone but its performance was found to be unimpaired after remagnetization.

Noise Monitoring

The originally contemplated use of the JP-1 equipment as a monitor for detecting self-noise, although very helpful in many instances, did not prove entirely successful because the single hydrophone was insufficiently sensitive to sounds originating in certain portions of the boat, particularly aft of the conning tower. For this reason a separate development program was initiated which led to the design and construction of supplemental equipment known as the *noise level monitor* [NLM].[b] This equipment provides a metering and switching adapter unit for the JP amplifier and utilizes four small hydrophones mounted at intervals along the pressure hull.

FIGURE 3. JT sonar equipment.

JT Sonar Equipment

The JT sonar equipment developed by CUDWR-NLL is designed to detect and determine the bearing of surface ships from submarines. Its 5-foot hydrophone is an electrically split, permanent-magnet magnetostriction unit, with lobe reduction. A sonic listening amplifier normally uses the sum of the signals from the hydrophone halves. An RLI unit uses the sum and difference signals to present a meter indication of hydrophone deflections off target. Power training and bearing repeater mechanisms provide hydrophone rotation at speeds of up to 4.5 rpm and transmission of hydrophone bearings to the conning tower. A talkback system provides two-way voice communication between the forward torpedo room and the conning tower and transmits sonar signals from the listening amplifier to the conning tower.

10.6 DEVELOPMENT

The JT development was a process of evolution in which each functional component was

[b] Described in Division 6, Volume 18.

carried through successive stages of research, design, construction, and tests of models, with the preparation of specifications proceeding as rapidly as possible. At intervals, combinations of components were assembled and tested to keep the complete system in balance. Although in practice there were no sharp lines of demarcation between apparatus and system development, the development of each major component can be discussed separately.

Hydrophone

The following hydrophone characteristics were considered to be of primary importance: (1) adequate sensitivity and smooth response over a wide frequency range, (2) maximum directivity consistent with a practically useful size and the frequency band to be used, (3) adaptability to use with an RLI system, (4) reduced side lobes and, (5) elimination of the necessity for periodic remagnetization.

Data and experience indicate conclusively that, for long-range detection of surface vessels, the use of sonic frequencies is preferable to the use of supersonic frequencies. As it was desired that the detection ranges obtainable with the JT system be at least equal to those of the JP equipment, it was decided to continue use of the band from approximately 0.5 to 10 kc for search listening. The range 5 to 9 kc was selected, on the basis of analysis and preliminary tests, as suitable for operation of the RLI for accurate bearing determination. In these ranges, the characteristic of the straight magnetostriction hydrophone is smooth, rising with octave, which compensates for the normal drop frequency at the rate of about 5 to 6 db per of 5 to 6 db per octave in the characteristic of ship's screw noise and normal background water noise.

Work was consequently directed toward improvement of the JP magnetostriction hydrophone and led to the development of the NL-124 unit[c] which was selected as suitable for use with the JT system. This hydrophone, a permanent-magnet magnetostriction unit 5 feet long, is electrically split into two halves for use with an RLI unit and is made up of 10 sections wound to yield a side-lobe reduction (difference between responses of the main lobe and the greatest side lobe) of approximately 25 db for a single frequency tone. The sensitivity of the NL-124 unit averages about 15 db higher than that of the JP hydrophone, thus making the signal-to-noise requirements of the first amplifier stage less stringent and allowing the use of lower overall gain in the system. The construction details of the NL-124 hydrophone are indicated in Figure 4 and the frequency response characteristics of a typical unit with and without a baffle are shown in Figure 5.

Later tests were made on another hydrophone similar to the NL-124 but wound with less taper to provide an intermediate value of lobe reduction. In this unit the greatest minor lobes were approximately 19 db less sensitive than the main lobe. Measurements using the noise band 5 to 9 kc showed the width of the main lobe at the —3-db point to be only 11 per cent greater than in the case of a unit without lobe reduction, whereas in the fully delobed NL-124 hydrophone the width of the main lobe is increased 20 per cent. On the basis of these tests it was decided that a lobe reduction greater than 18 to 20 db could be attained only by disproportionate increase in the width of the main lobe. However, since steps had already been taken toward production of the NL-124 hydrophone, this unit was retained for use with the JT system.

Baffle

In developing a baffle for use with the NL-124 hydrophone it was considered desirable (1) to increase the front-to-back discrimination over that provided by the JP baffle and (2) to improve its streamlining.

Calculations indicated that for maximum discrimination above 500 c the cross section of the baffle should be at least 4 inches in height by 10 inches in depth, including the 2½-inch diameter of the hydrophone. Acoustic and hydrodynamic tests of models led to the conclusion that a teardrop section of these proportions would most adequately meet the requirements in both respects.[3]

An experimental cast-bronze baffle, weighing 150 pounds, was discarded in favor of a lighter unit fabricated from stainless-steel

[c] Described in Division 6, Volume 13.

sheet stock. This baffle, with the same shape, dimensions, and equivalent strength characteristics, weighed only 48 pounds. As with the JP of ¾-inch Cell-tite rubber. The directivity patterns (with halves connected series aiding and series opposing) of the NL-124 hydrophone

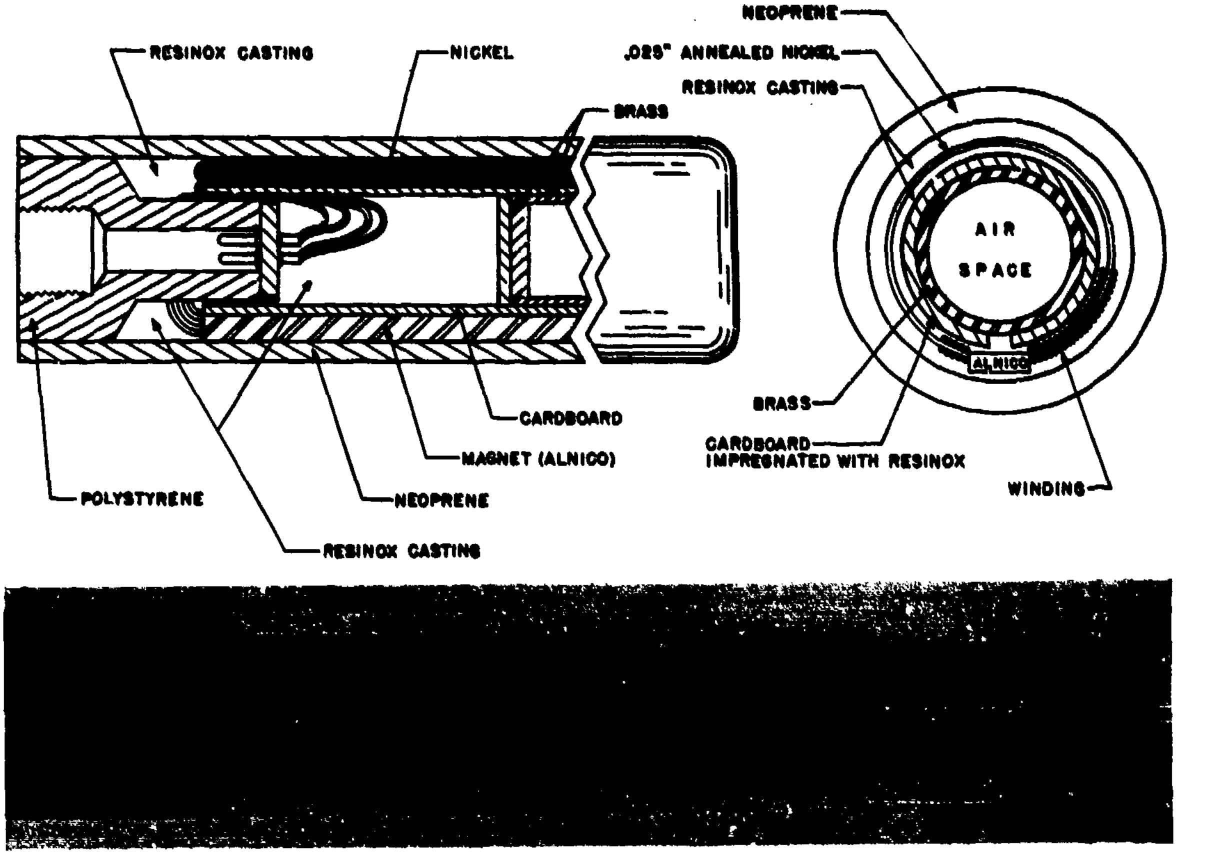


FIGURE 4. Construction details of JT hydrophone.

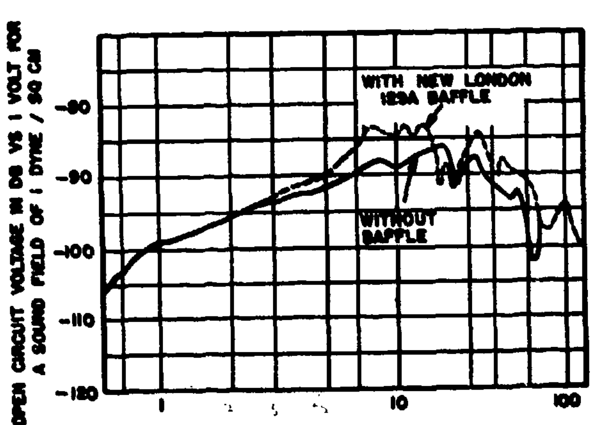


FIGURE 5. Frequency response characteristics of JT hydrophone with and without baffle.

baffle, the metal fairing is hollow and free flooding. Pressure release is provided by a blanket made of $\frac{1}{16}$-inch neoprene over a filler equipped with this baffle are shown in Figure 6. These were measured using a 5- to 9-kc noise band as a source and indicate an improvement of 6 db in front-to-back discrimination compared to that of the JP hydrophone and baffle in the same frequency band.

Sound Absorbing Coupler

Hull vibration transmitted to the hydrophone through the metallic support and training system of JP installations limited target detection from many of the noisier submarines. Several methods were considered for isolating the hydrophone from vibration or shock applied to the shaft without loss of sufficient torsional stiffness to retain the bearing accuracy of the system.

It was decided on the basis of preliminary

experiments to use a sandwich-type coupler, consisting of two brass plates or disks with a layer of rubber between them. Calculations were made to determine the theoretical attenuation produced by various grades and thicknesses of rubber. These indicated that approximately 1 inch of rather soft rubber (25-30 durometer) would be required to suppress frequencies down to 200 c. However, the best bond to brass was obtained with rather hard rubber or neoprene of at least 40 durometer. Several samples of various grades of neoprene from 30 to 50 durometers were tested in tension and shear and on a shake table. In the harder samples the bond had a tensile strength of 340 psi and withstood vibration of ⅛-inch amplitude at 1,000 c for 8 hours with no evidence of fatigue. Listening tests indicated that, when using the 500-c high-pass filter of the JP amplifier, the coupler produced a noticeable improvement at submarine speeds up to 3 knots. At higher speeds no improvement was observed, presumably because of turbulence or waterborne vibration transmitted from the hull to the hydrophone.

Disk recordings of submarine background noise made at various submerged speeds indicated that at 3 knots the greatest vibration was in the 100-c to 200-c band, with the energy decreasing at higher frequencies to a negligible value at 3,000 c. It was found in dockside tests that a 28-durometer coupler attenuated all frequencies above 170 c by 10 to 15 db and that a 50-durometer coupler attenuated all frequencies above 300 c by an average of 8 db. A double mounting was accordingly constructed on a submarine to allow direct comparison under actual conditions. Listening tests and recordings were made at 2 knots, 4 knots, and 6 knots in relatively quiet water 100 fathoms deep. Under these conditions, a coupler with 25- to 30-durometer rubber provided a reduction of up to 6 or 8 db in the background noise from auxiliaries and training gear. The tensile strength of this brass to soft rubber bond was 120 psi, judged to be adequate since there were 70 square inches of area. Nonetheless, three rubber-cushioned safety bolts provided protection against loss of the hydrophone through any possible casualty to the bond. The torsional stiffness of the coupler was such that the torque created by water forces on the JT hydrophone

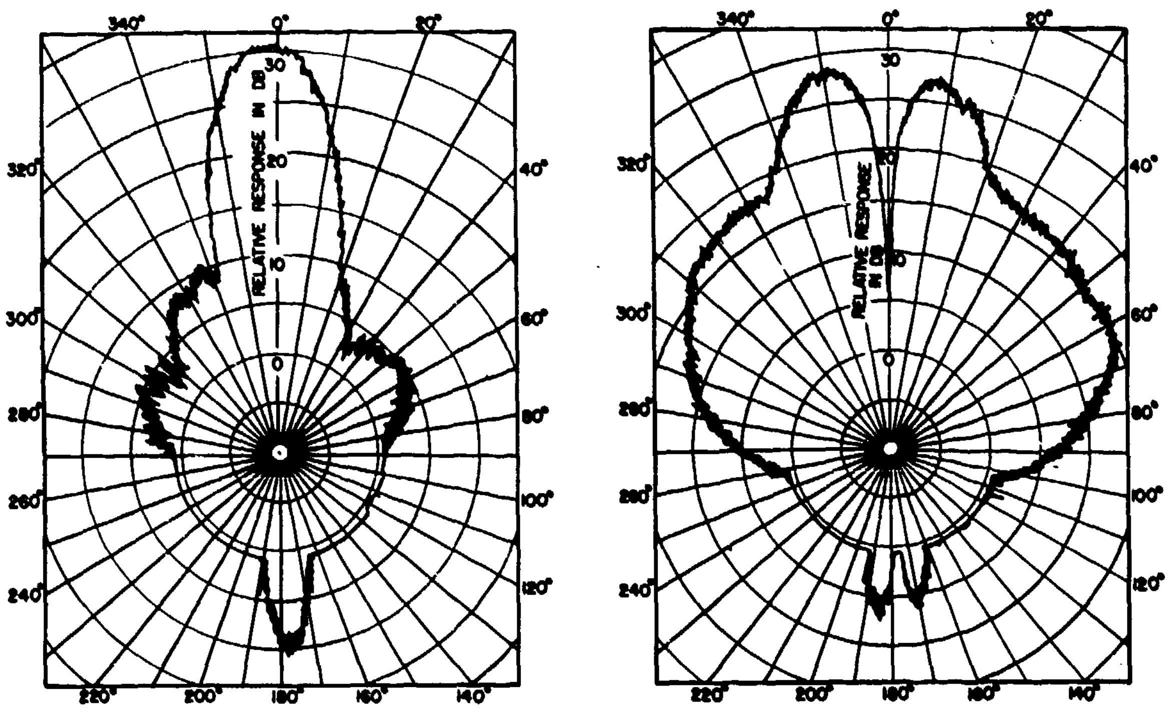


FIGURE 6. Directivity patterns of JT hydrophone assembly: (Left) Series aiding and (right) series opposing.

and baffle at the critical bearings could cause a maximum deflection of 0.1 degree at 3 knots and 0.35 degree at 6 knots.

RLI and Listening Amplifier

Tracking a target with JP or WCA equipment requires the operator to sweep the hydrophone beam across the target. Only intermittent bearing information, having an average accuracy of about ± 1.5 degrees, is provided. An investigation of methods to improve this condition, for use in the *triangulation listening ranging* [TLR] system discussed in Chapter 12, included the analysis of several types of *bearing deviation indicators* [BDI], all of which are based on the difference in arrival time of sound at the two halves of a split hydrophone. In the selected circuit, designated RLI, separate signals from the hydrophone are fed into a transformer network which takes the vector sum and difference of the signals as indicated in Figure 7. Before amplification, the sum and

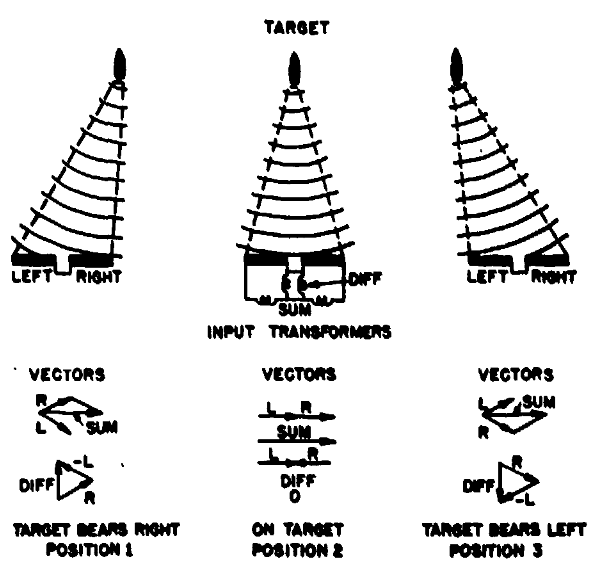


Figure 7. Vector relationships at RLI input.

difference signals are separated ± 90 electric degrees for the off-target conditions indicated as positions 1 and 3. By means of additional electronic equipment terminated by a zero-center meter, a direct visual indication of whether the hydrophone is on target or requires right or left training is presented to the operator.

A prototype model was designed which provided good response between 0.5 and 14 kc to permit extending the frequency band above the originally selected 5- to 9-kc band should system tests prove this desirable.

A block schematic of this RLI unit (also representative of pilot models and production units) is shown in Figure 8. Signals from the sum and difference input transformers are amplified before passing through 0.5 to 14-kc band-pass filters provided to attenuate l-f noise and h-f echo-ranging signals. Special attenuators control the gain of the two RLI channels either manually or by means of an *automatic volume control* [AVC] circuit. The signals are further amplified and passed through 5- to 9-kc band-pass filters, after which phase-shifters in each channel produce a net advance in phase of 90 degrees for the difference channel. The signals in the two channels being formerly in quadrature, the additional 90-degree phase shift results in signals in the sum and difference channels which are either in phase or 180 degrees out of phase.

Both channels are further amplified and the sum channel is phase-inverted prior to rectification of both signals by a phase-sensitive detector. The rectified d-c signal is negative if the sound source bears to the right of the hydrophone and positive if the sound source bears to the left. A d-c amplifier increases this signal to operate a zero-centered microammeter. When an average target signal is 1 degree off hydrophone bearing, the meter is deflected full scale.

The listening channel is a separate amplifier (without AVC) which normally connects to the sum channel but may be connected to the difference channel momentarily. A separate volume control and standard high-pass filters are provided; a two-stage amplifier supplies audio power for two high-quality dynamic headsets. This audio signal is also supplied to the sonar talkback system described in a later section.

Supersonic Converter

The broad frequency characteristic of the straight magnetostriction hydrophone and its sharp directivity above the sonic band are used to advantage by the addition of a small super-

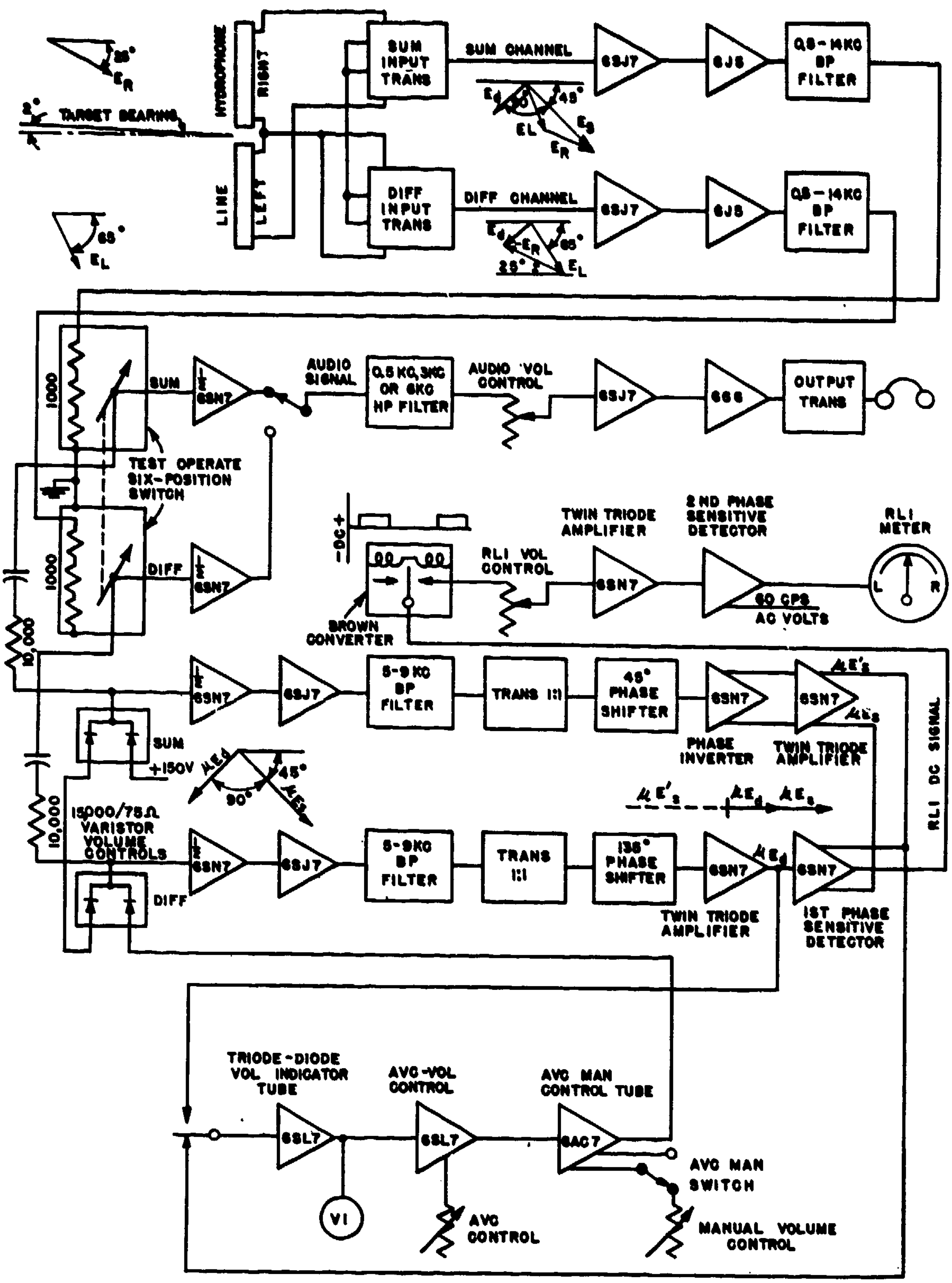


FIGURE 8. Block diagram of JT sonar RLI circuit.

sonic converter unit. The benefits derived are: (1) the ability to pick up enemy signals outside the 14- to 36-kc band of the QB-QC receiving equipment or to serve in case that equipment became inoperative and (2) the ability to discriminate between closely spaced targets by listening to the higher frequency components of screw noise.

and bridges across the volume control of the JP amplifier.

Several vernier condensers are required to adjust the oscillators to the correct frequency. These oscillators utilize a resistance-stabilized circuit and vary but slightly in frequency for changes in line voltage. The band-pass filter is inductance-tuned at the factory and usually requires no further adjustment. All five tubes in the circuit are of the 6SJ7 type, which simplifies tube replacement. The heater current of these tubes is controlled by a regulator tube to reduce the effect of variations in line voltage.

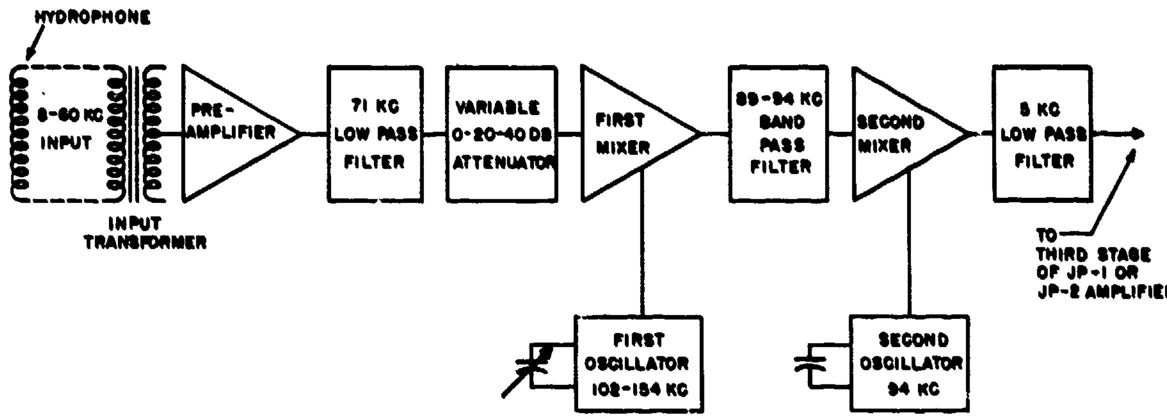


FIGURE 9. Block diagram of supersonic converter components.

A supersonic converter, or converter-amplifier, provides for converting any 5-kc band in the 8- to 65-kc region to the audible band 0.1 to 5 kc. A block diagram of the circuit is shown in Figure 9. Signals from the hydrophone are transformer-coupled to a single-stage amplifier terminating in a 71-kc low-pass filter. This filter reduces any extraneous signals resulting from stray coupling of the input stage to the two heterodyne oscillators. A three-step attenuator provides a means of reducing the level of echo-ranging signals to prevent overloading the grid of the first mixer tube. The first mixer is coupled to a heterodyne oscillator which may be tuned from 102 to 154 kc by means of a condenser coupled to the panel tuning dial. The output of the first mixer is terminated in a high-impedance band-pass filter which accepts the heterodyned signals in the 89-kc to 94-kc pass band. These signals are connected to the input of a second mixer stage which is modulated by a 94-kc fixed oscillator. The 89-kc to 94-kc signals, therefore, are heterodyned down to a 0-5-kc band in the second mixer. The output of this mixer stage is terminated in a 5-kc low-pass filter which also attenuates extraneous signals. This filter is terminated in 10,000 ohms

POWER TRAIN, DRIVE, AND BEARING REPEATER SYSTEM

The development of these components involved the selection of training equipment and the detailed design of drive and bearing repeater facilities, which could be installed conveniently in approximately 200 submarines. Numerous surveys, layouts, and discussions were necessary in order to anticipate the problems imposed by a variety of forward torpedo-room arrangements.

Training Gear. Three designs of JP training gear in use were designated as Old Portsmouth, New Portsmouth, and Mare Island types. Because of the high torque required at depths greater than 100 feet, replacement of the Old Portsmouth type was undertaken early, and action was later taken to standardize the Mare Island type for all new boats.

The proposed use of the 5-foot hydrophone

assembly made it necessary to consider the ability of the JP training shafts to withstand larger forces. Calculations and tests were made of the probable water drag, overturning moment, bearing loads, torsional moment, and deflection in the shaft at speeds up to 9 knots. These indicated that the deck structure and shafts, while not ideal, were satisfactory. These studies also enabled the power requirements to be established. On the basis of a maximum training speed of 5 rpm, a maximum training effort equivalent to 6 pounds applied at the handwheel through the standard 11-to-1 gearbox, and a reserve power of over 500 per cent for contingencies, a ¼-hp drive motor was selected.

One experimental training system having slewing-type control was tried out, but experience soon proved that a follow-up type control in which one revolution of the handwheel would rotate the hydrophone approximately 10 degrees was preferable. Several types of training systems, including thyratron, hydraulic, and amplidyne, were considered from the standpoints of overall performance, development time required, space, inherent noise, and availability. An amplidyne system was chosen in which direction and speed of rotation are remotely controlled by means of small manually operated handwheels coupled to 5CT synchros. A simplified schematic of the elements is shown in Figure 10.

The training motor is a gear-head d-c motor rated at ¼ hp at 155 rpm. A follow-up synchro (5G) is mounted by means of a bracket from the motor end bell.

Power from the gear-head motor is transmitted to the JP gearbox by means of sheaves and two V belts. A hinged handle on the large sheave of the training gear shaft makes manual training possible. Such a belt drive simplifies installation problems and reduces mechanical vibration transmitted to the hydrophone shaft. This drive rotates the hydrophone at any speed up to 4.5 rpm, depending upon the rate of turning the handwheel. One revolution of the handwheel trains the hydrophone approximately 10 degrees.

Bearing Repeater System. The bearing repeater equipment, a schematic diagram of which is shown in Figure 11, transmits the relative bearing of the JT hydrophone to the repeaters associated with the *target designation system* [TDS], the *torpedo data computer* [TDC], QB, and QC-JK portions of the WCA-type equipment in the conning tower, and to the repeater in the JT console. A size 6G synchro, geared in a 1-to-1 ratio with the hydrophone shaft supplies all the one-speed repeaters; a size 5G geared 36-to-1 with the shaft supplies the 36-speed repeaters.

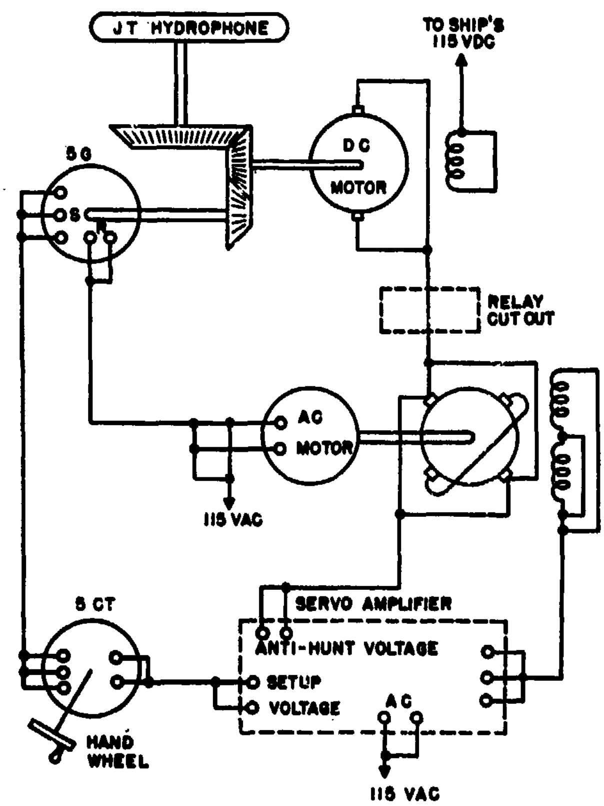


FIGURE 10. Schematic diagram of JT power training system.

JT-gyro switch boxes, mounted on top of the QB and QC-JK remote-control units provide a means of bearing presentation to the QB and QC-JK operators. For example, when the switch is in the JT position, relative JT bearings are indicated by the North indicator on the compass card.

Sonar Talkback System

To provide communication between the sonar operator in the forward torpedo room and the attack team in the conning tower, tests of ex-

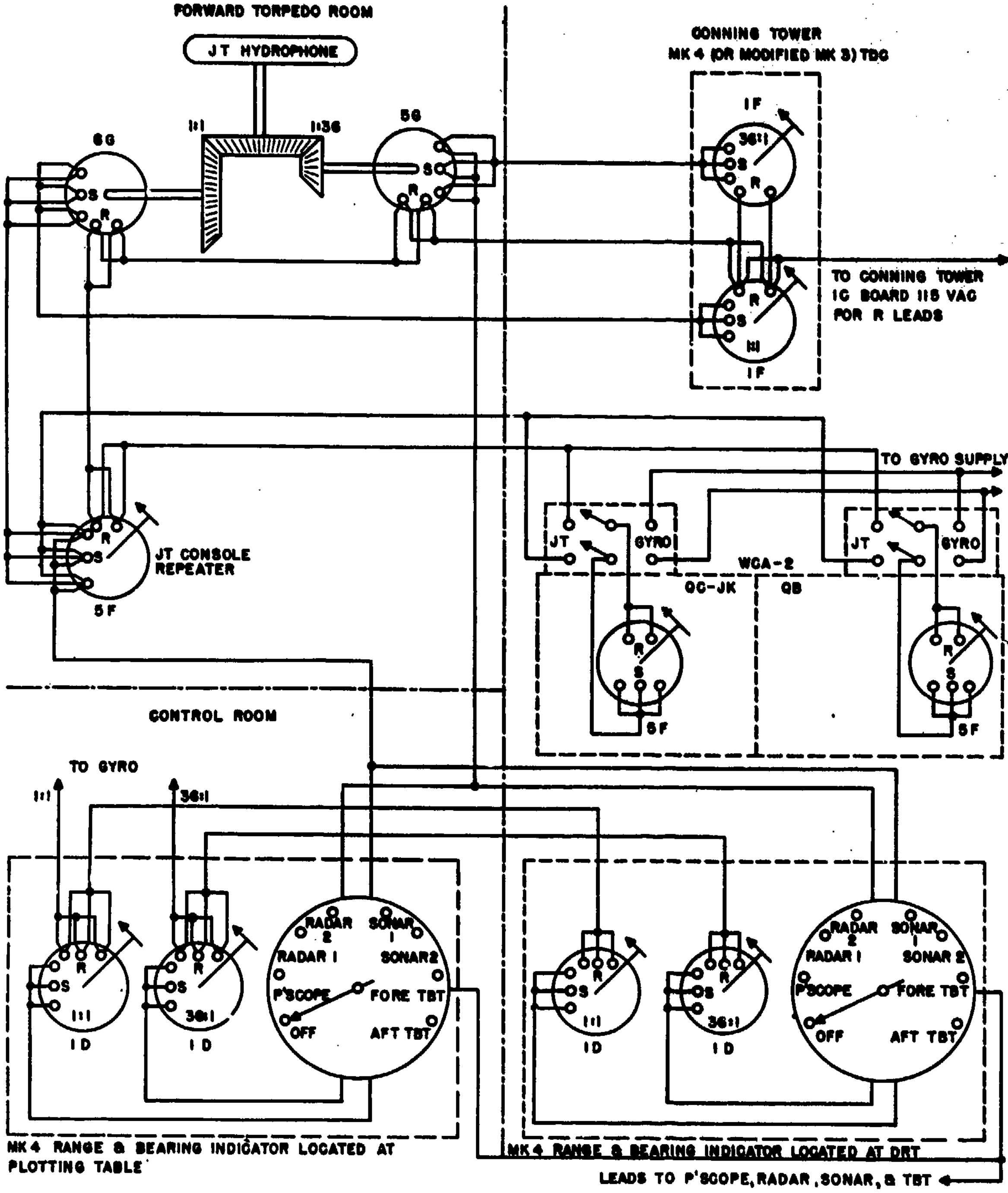


FIGURE 11. Schematic diagram of JT bearing repeater system.

perimental equipment installed on fleet submarines indicated the need for: (1) provision of direct two-way communication with ability to transmit the sonar signals to the conning tower when desired, (2) provision of a separate amplifier for the communication system, (3) use of the spare battle phone circuit cables (XJA) to facilitate installation and, (4) use of a 110- to 120-volt d-c power supply to permit operation on all boats during evasive maneuvers. It was also considered essential that voice communications from the conning tower and

the signal from the sound gear should reach the JT operator over the same headphones and that the sonar signal should be received continuously by the operator except when messages are being transmitted from the conning tower.

Intelligibility tests and characteristic curves were run on various microphones, amplifiers, speakers, and headphones to determine the components most desirable for good articulation. A dynamic Permoflux Type PDR-8 headphone was selected on the basis of response characteristic and rugged construction to replace the less rugged crystal-type phones used with the JP equipment. The same type of receiver was also found to be almost ideal for use as a microphone.

Before the JT equipment was completed, a talkback system, which could be installed separately (for use with the JP gear and later with the JT gear), was designed. The system consists of four units: sonar talkback amplifier (Navy Type CRV-50200), talkback control unit (CRV-23461), talkback speaker unit (CRV-49590), and headset (CRV-49586).

Amplifier. The amplifier, a three-stage, resistance-coupled, feedback unit, is installed with the sonar gear in the forward torpedo room. Screwdriver adjustments regulate volume.

Talkback Control Unit. The talkback control unit, also installed in the forward torpedo room, contains the power supply switch, fuse, pilot light, and jacks for the sonar operator's headset and spare headphones. Switches are also incorporated for controlling voice and sonar signal transmission to the conning tower.

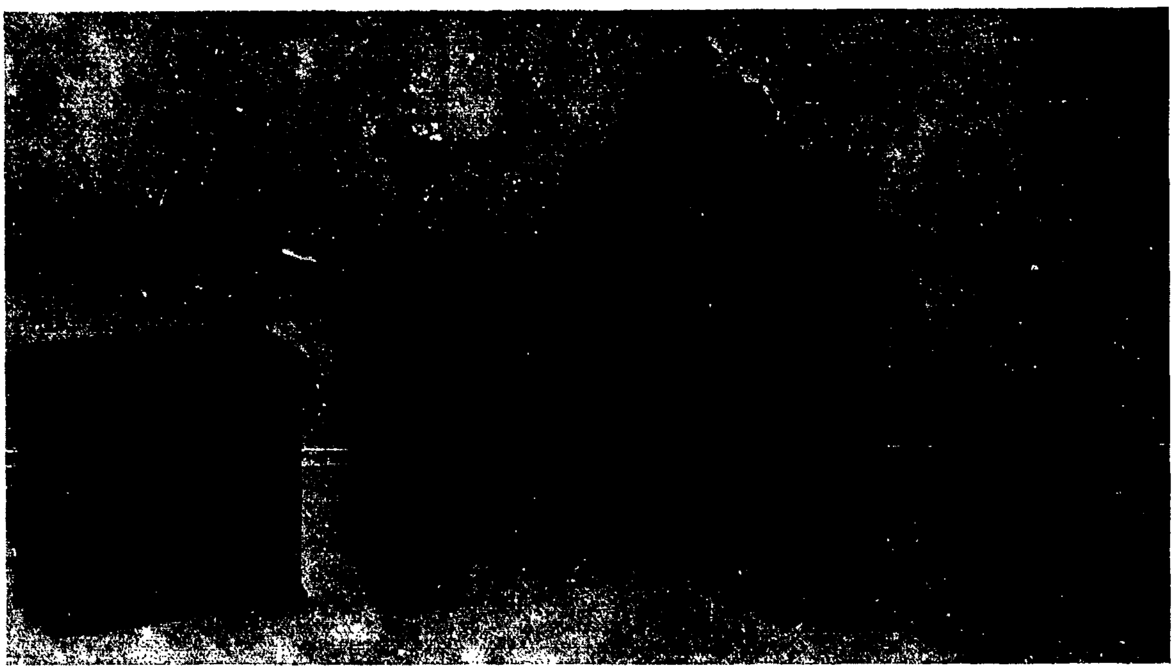


FIGURE 12. Components of sonar talkback system.

Talkback Speaker Unit. The talkback speaker unit, installed in the conning tower, utilizes a 6-inch permanent-magnet type speaker with a moistureproof cone and contains a jack for headphones. A switch is provided in the speaker unit to control a relay for reversing the sound circuit, making it possible to communicate from the conning tower to the sonar operator by using the speaker as a microphone.

Headset. The headset used by the sonar operator contains three dynamic headphones, with the third unit, supported on a wire frame from the headband, being used as a microphone. The four units of the talkback system are shown in Figure 12.

10.7 TEST AND CALIBRATION FACILITIES

In addition to the development of components of the JT system itself, consideration was given to the problem of providing for testing and adjusting the equipment in the field. It was concluded that a portable test set should be made available at bases and tenders to enable technicians and field engineers to check and maintain the electronic components of the JT system at the time of installation and during refit periods.

The test set finally evolved consists of an attenuator and phase-shift system and an electronic noise source. The voltage for the attenuation and phase-shift system may be derived from either the self-contained noise source or from a conventional externally-connected audio oscillator. A meter is provided on the panel for calibrating the level at the input of the attenuator. The output voltages, the phase of which may be altered as previously mentioned, are taken across 1-ohm resistors. The output may be varied in amplitude from -130 db to -40 db below 1 volt in 1-db steps. Each unit is provided with a set of cables and terminations to permit accurate measuring of the gain and phase-sensitivity of the RLI system and the sensitivity of the JP amplifier and supersonic converter.

Because the JT system is intended to indicate target bearings accurately, it is essential that the hydrophone and associated equipment be aligned with the hull so that sound and periscope bearings agree as closely as possible. Complete agreement between sound and periscope bearings is not attainable under all conditions because of factors such as sound travel time, parallax errors, and acoustic shielding from the conning tower. It is also highly desirable that the sound operator be able to check the performance of the system periodically during war patrol.

It was believed possible to meet both these requirements by providing a sound source on the submarine at a fixed known bearing from the JT hydrophone.

To accomplish this, an NL-130[d] hydrophone (used as a projector) is mounted on the radio mast and energized by a small electronic noise generator capable of producing a broad-band signal similar to propeller noise. Tests of this equipment on submarines indicate that, at speeds below 3 knots, RLI bearings can be obtained to within ± 0.2 degrees on the reference source. A production unit of this bearing calibration equipment is designated as the sonar test target and is intended for use with the JP, JT, and WFA gear.

[d] This unit is described in Division 6, Volume 11.

10.8 EXPERIMENTAL SYSTEM AND LABORATORY PILOT MODEL

During the JT sonar development program the components of the system were thoroughly tested at sea both separately and in various combinations. An experimental system incorporating most of the major components of the final JT model but utilizing a split magnetostriction hydrophone consisting of two 18-inch wood-core elements, was used in an extensive test program. This system, first bench-tested in the laboratory and sea-tested on a surface vessel, was subsequently installed on a submarine for exhaustive tests of bearing accuracy and evaluation of its tactical effectiveness.

During these tests, also, investigation was made of a system for automatic control of the hydrophone bearing with the RLI signal as a control voltage. This feature, known as the *automatic target follower* [ATF], was abandoned after preliminary tests because of unsatisfactory performance on closely spaced multiple targets and because the necessity for freezing the system design prohibited further development work.

An indication of the degree of bearing accuracy attained during tests of the experimental system is shown in Figure 13, which records the results of a typical check between sonar and periscope bearings for an approximately circular target vessel course. Other tests of this equipment on a submarine indicated that it was possible for an operator, after very little instruction and practice, to track single targets out to 10,000 yards with an accuracy of ± 0.5 degree.

A study of the effects on RLI bearings of interfering targets of varying intensities and

angular relationships with respect to the desired target indicated that appreciable bearing errors are introduced when high-level interfering signals are separated from the desired target by angles less than that between the on-target and secon··ary zeros of the RLI pattern

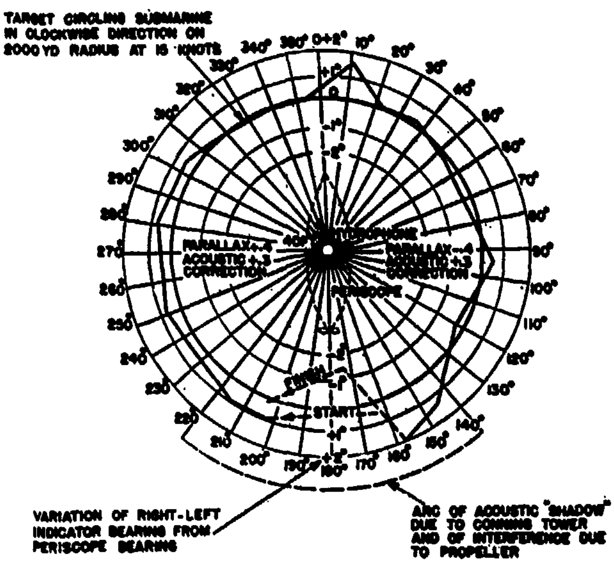


FIGURE 13. Bearing accuracy obtained in experimental system tests.

(about 17 degrees for the NL-124 hydrophone in the band 5 to 9 kc). For this reason, consideration was given to reducing the RLI lobe width by use of a 7- to 12-kc band and a hydrophone having a smaller value of side lobe reduction than the NL-124 unit as discussed earlier. It was believed that production might be delayed by incorporation of these changes, however, and the 5- to 9-kc band and NL-124 hydrophone were retained.

10.9 MANUFACTURER'S PILOT MODEL

With the laboratory pilot model as a guide, the Radio Corporation of America constructed five units of a pilot model preliminary to undertaking full production of the JT sonar system. Three of these units were installed on new-construction submarines at New London, Portsmouth, and Mare Island.

Tests of the manufacturer's pilot model units during the training periods of the submarines indicated satisfactory performance, the results being about as expected on the basis of the experimental system and laboratory pilot model. It was established that (1) the RLI is very helpful in maintaining accurate bearings on single targets, (2) the supersonic converter enables the operator to discriminate between targets separated by as little as 3 or 4 degrees, (3) the power drive enables the operator to train the hydrophone accurately and without appreciable physical effort and, (4) the sonar talkback and bearing repeater systems permit close coordination between the sound operator and the attack team and enable the QB or QC operator to preset the projector bearing to aid in obtaining single-ping ranges.

10.10 PRODUCTION MODEL

The production units of the JT sonar equipment closely follow the design of the laboratory and manufacturer's pilot models. The system is made up of five major assembl··s: master control unit, power training and ·earing repeater equipment, hydrophone assembly, supersonic converter, and the sonar talkback equipment.

The master control unit, Figure 14, including the RLI, the listening components, and the control facilities, is the largest unit in the JT sonar system. It has a space requirement of 19$\frac{5}{16}$ inches width, 16$\frac{1}{2}$ inches depth, and 37$\frac{1}{2}$ inches height, including the height of the shock mounts, three on either side of the base, which isolate the unit from the deck. All components are contained in two metal cabinets which are attached and interwired. The lower cabinet contains a steel chassis 8 inches deep hinged to the cabinet at the bottom edge. The larger components, including the tubes, are mounted on the rear of this chassis so that the wiring, resistors, and similar parts are accessible from the front to facilitate servicing. The lower portion of the chassis is covered with a separate panel attached with thumbscrews and the upper portion is covered by a hinged panel on which are mounted the circuit controls.

At the top of the unit is the control cabinet having a sloping front and a 3-inch extension beyond the rear of the lower cabinet to provide an entrance for connecting cables to the main terminal board mounted inside the rear of this

cabinet. The chassis may be pulled forward on slides giving access to the main terminal board in the rear and to the components mounted on the chassis and panel.

The power training handwheel, coupled to an inertial flywheel and a control transformer

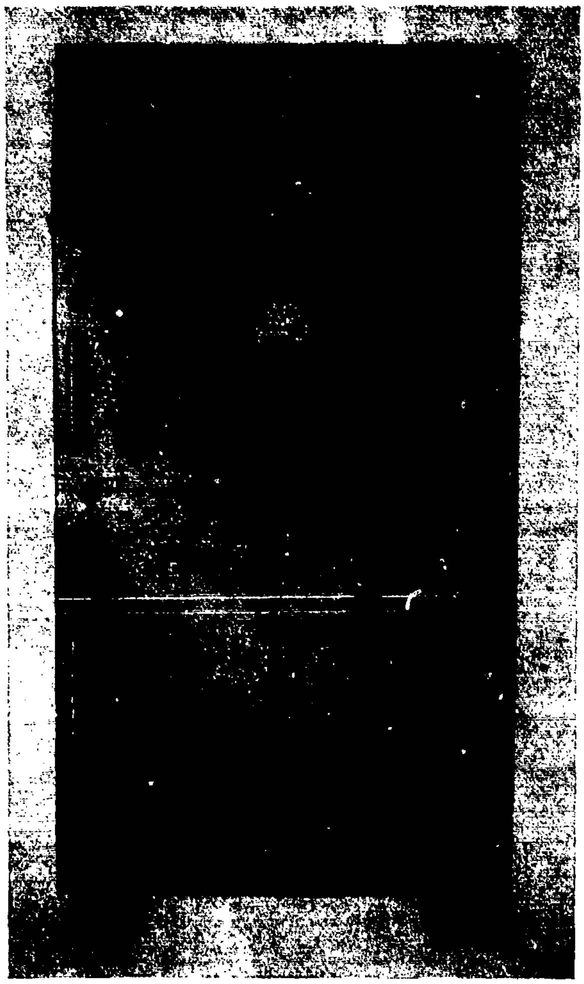


FIGURE 14. JT sonar master control unit.

(5CT), is mounted at the right on the vertical portion of the upper chassis beneath the sloping panel, and on the left of the chassis is the amplidyne power training amplifier. The RLI meter is mounted at the center of the panel with the hydrophone relative bearing repeater dial just above it in the same window. In a separate window below the meter is a reciprocal bearing dial. Internal lighting is provided for the meter and dials. On the left side of the sloping panel are located the jacks and switches of the sonar talkback control unit (see development section). The bearing repeater synchro (5F) is mounted in a casting attached to the rear of the panel.

The hydrophone assembly, weighing about 180 pounds, consists of the hydrophone, baffle, and sound absorbing coupler shown assembled in Figure 15.

FIGURE 15. JT hydrophone assembly.

The 5-foot hydrophone, bolted to the training shaft flange, is made up of five pairs of permanent-magnet type cylindrical hydrophone elements 5¾ inches in length and 1¾ inches in diameter assembled coaxially on a rigid brass tube. A cylinder of cardboard between the brass tube and hydrophone units provides a pressure release to assure good acoustical performance. The hydrophone is described as a delobed type, since each pair of units on opposite sides of the center is reduced in sensitivity by reducing the number of turns successively from 245 for the center pair to 95 turns for each end unit. The assembly of hydrophone elements is encased in a 2½-inch diameter ¼-inch thick neoprene cylinder and impregnated with a Resinox compound. A polystyrene connection jack and gland seat is inserted in one end to connect with a four-wire plug and a four-conductor shielded hydrophone cable. A gland assembly seals the cable entrance and facilitates replacement of the hydrophone after initial installation.

The baffle is a streamlined, stainless-steel fairing 64½ inches long, 4 inches high, and 9¾ inches wide. It provides a mount for the hydrophone and a form for attaching a ¾-inch Cell-tite rubber blanket which reduces the back-sensitivity of the hydrophone 18 to 20 db in the 5- to 9-kc frequency band.

The coupler consists of 2 brass disks 10 inches in diameter and 1 inch thick, bonded together with a 1-inch layer of 25 to 30-durometer rubber. Precautions are taken to obtain a strong durable bond which is not susceptible to changing climatic conditions or the deteriorating action of salt water. Three rubber-insulated through-bolts safeguard against loss of the hydrophone if the rubber bond fails. The baffle is secured to the top of the coupler.

10.11 PERFORMANCE

Tests of the experimental JT models as well as several manufacturer's pilot models showed that the improvements over the JP gear add to the ease of operation and the speed with which data can be transmitted. Corroborating patrol reports which indicate performance under actual battle conditions are not yet available.

Chapter 11

THE 692 SONAR SYSTEM

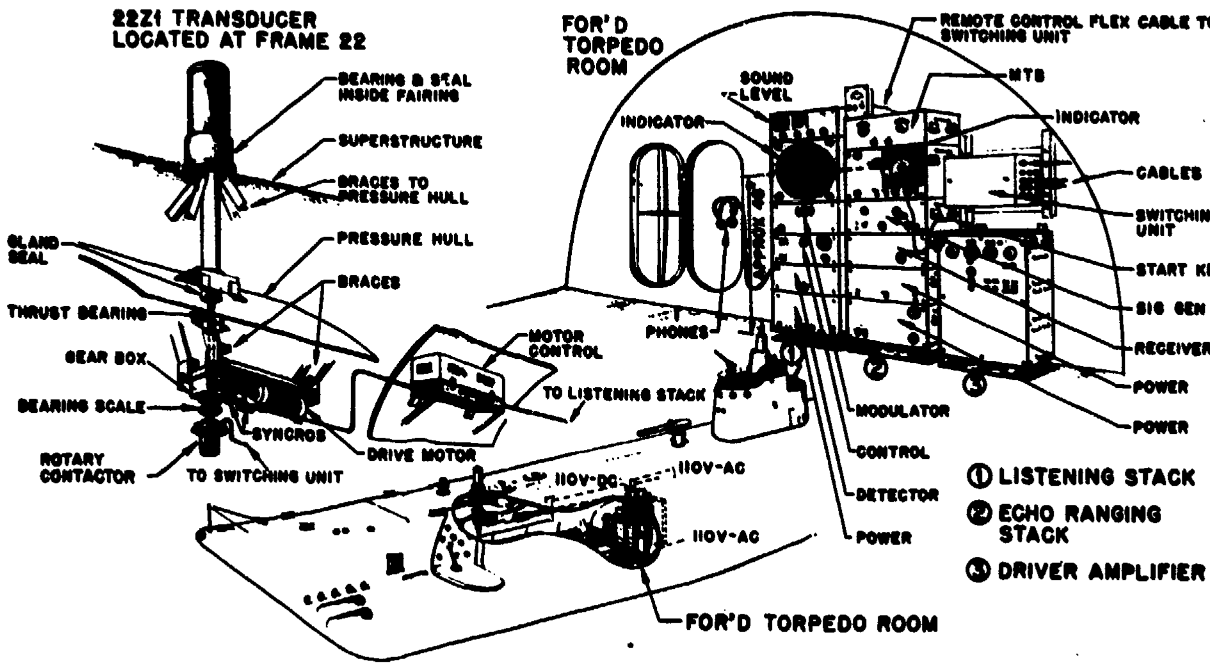


FIGURE 1. Positions of 692 submarine sonar system components.

The 692 sonar, designed by Bell Telephone Laboratories, is a multipurpose experimental system designed for submarine use. Utilizing the WFA three-section crystal projector, it provides for listening over the band 200 c to 60 kc with bearing deviation indication for frequencies between 15 kc to 60 kc. Other features include maintenance of true bearing [MTB], automatic target following, automatic torpedo detection, and self-noise monitoring. It also proposes QBF-type echo-ranging equipment to operate over the range 10 kc to 50 kc and modified to provide short-pulse mine detection with plan position indicator [PPI] presentation. Although the development program was not concluded, preliminary operational tests of the listening system showed good sensitivity and bearing accuracy.

11.1 INTRODUCTION

At the time work was begun on the 692 sonar system, the standard systems in use on submarines were rather limited in scope. They consisted for the most part of a JK-QC projector combination for listening and echo ranging over a fairly narrow band of frequencies in the region of 25 kc. This was supplemented by the JP system, which was entirely separate and covered the audible range. Later adaptations extended the JP into the supersonic range. The training mechanism used with the JK-QC projector did not permit the rapid scanning needed to identify low-intensity signals. The JP was trained manually and could differentiate signals but required considerable physical effort. None of these systems employed visual bearing indicators of the phase-sensitive type. The echo-ranging available with the QC projector was the standard 25-kc long pulse type used in antisubmarine work.

Looking toward improved submarine sonar systems, the outstanding need was for a system which would supply information to the submarine commander operating below periscope

depth, comparable to what he can obtain with his periscope. The best possible sonar cannot equal the capabilities of periscope and radar. Low-frequency sonar may excel in range but can not compare in accuracy. High-frequency sonar can provide good accuracy but falls short in range. Since the important factor in deep operations is security, echo-ranging of any kind is not the final answer. Triangulation ranging on sound bearings is a possibility. Sound bearing accuracy then becomes of primary importance and a requirement of ± 0.1 degree is not unreasonable. This in turn imposes certain requirements on the training system as well as the projector. A complete sonar system should also include means for scanning mine fields, self-noise monitoring, torpedo detection, location of depth charges, sonic depth finding, and underwater communication.

The equipment designated 692 submarine sonar, from the OSRD contract number, was designed to facilitate the investigation of sonar requirements rather than to supply a working system. Its scope, therefore, is quite broad as regards component features, controls, and adjustments, and its parts are not completely integrated as they would be in a standard equipment.[a]

The original project called for the development of a listening system only, which was to be supplemented with a standard surface vessel type of echo-ranging equipment (QJB) operating at 24 kc and at 50 kc. Subsequently the project was enlarged to include the development of a short-pulse, high-peak power, echo-ranging equipment to operate over the range of frequencies from 10 kc to 50 kc. Finally, it was agreed to include in the echo-ranging system a *plan position indicator* [PPI] for mine detection.[b]

The initial requirements included continuous search at speeds up to 60 rpm with an indicator preferably not of the ***cathode-ray oscilloscope*** [CRO] type, rapid shifting between continuous search, and hand training, the latter to be accurate within $\pm$ 0.5 degree or better, using a phase-sensitive bearing indicator, automatic or aided target tracking, and ***maintenance of true bearing*** [MTB]. The self-noise of the training system was to be low enough so as not to affect listening. The listening system had to be capable of differentiating between two targets of the same intensity when they are 5 degrees or more apart. The frequency range was to be from 15 to 50 kc, with provision for listening to suitable bandwidths with both loudspeaker and headphones.

The completed system, which has been delivered to the U. S. Navy at New London, Connecticut, contains all the features outlined above. It includes a three-section projector which is a prototype of the projector used with the WFA sonar. This is one of several features which the two systems have in common and which were derived from the early development work on Contract No. 692. The indicator for the listening system displays the location of targets by means of an azimuth circle of lights and has proved adequate for tracking torpedoes. The MTB feature operates satisfactorily either with a step-by-step or synchro type of compass repeater. Either continuous search listening [CSL], automatic tracking [AUTO], or hand training [HAND] may be rapidly selected on one switch.

Measurements of the bearing accuracy of the automatic target tracking system at sea indicated a 0.15-degree standard deviation of sound bearings with respect to the stern of a target ship. This means that the bearing accuracy of the 692 sonar will be well within the $\pm$ 0.5-degree requirement. The self-noise of the training system is well below the lowest ambient noise levels at distances greater than 10 yards from the projector. The self-noise picked up by the projector is below the internal noise in the system except at frequencies below 1,000 c and at speeds in excess of 20 degrees per second. The internal noise is below the lowest ambient noise levels in the intermediate range of frequencies and only slightly above at the ends of the frequency range. The useful frequencies

[a] In order to include the 692 sonar system in this volume, it was necessary to confine this material to a generalized description of the system, omitting actual circuit details and operation. These generally follow component circuits described in this volume and Division 6, Volume 15. Complete information on actual circuits and their performance under experimental conditions may be found in reference 1, which has been microfilmed.

[b] Details of the echo-ranging equipment embodied in the 692 sonar are discussed separately in Division 6, Volume 15.

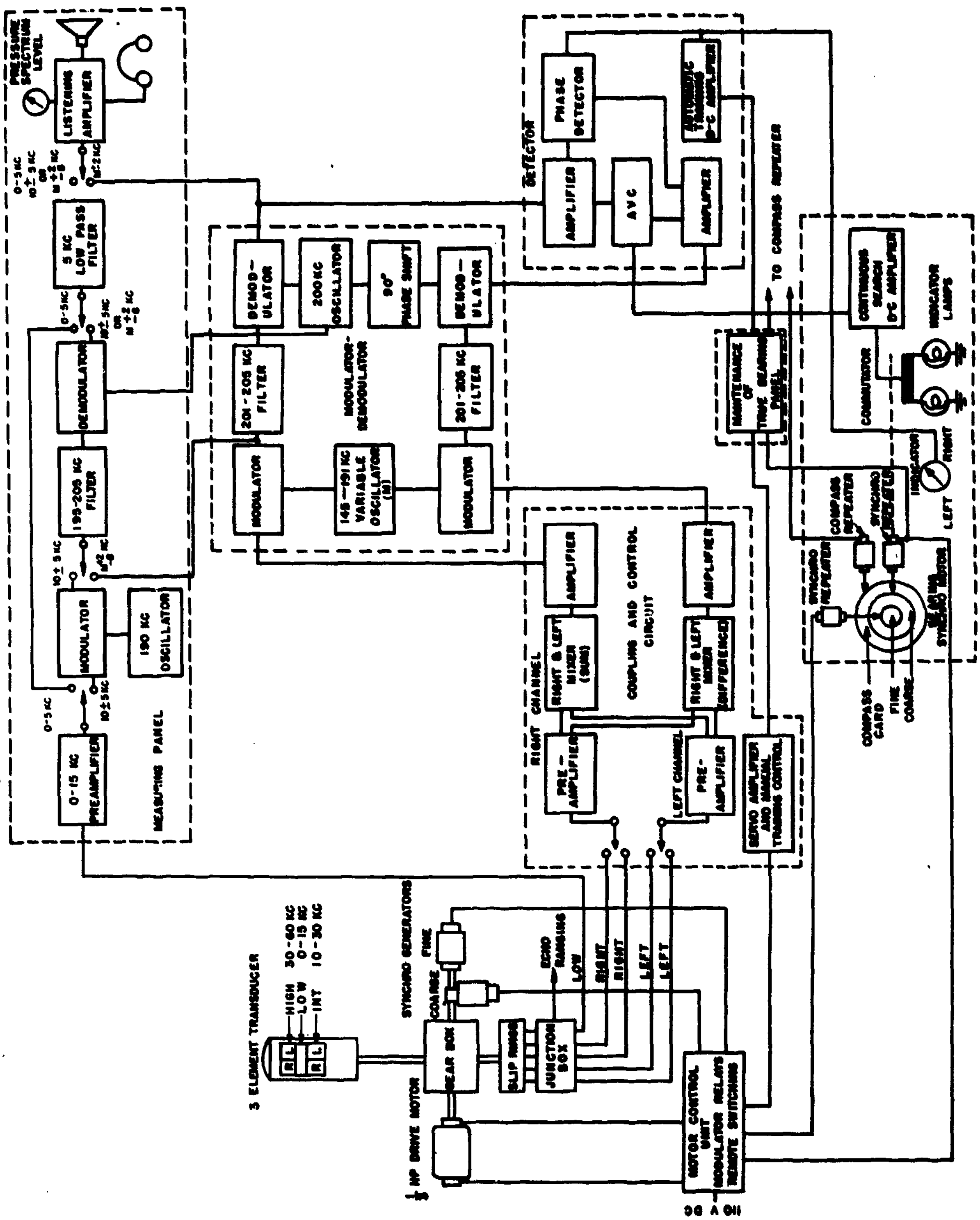


FIGURE 2. Block diagram of listening system.

extend from about 200 c to 60 kc, but the band below 10 kc is used only for detection listening and not for bearing determination, because of its poor directivity.

The ability of the system to differentiate between targets depends upon the beam width of the projector. By avoiding the use of side lobe reduction which broadens the beam, the discrimination at frequencies above 50 kc is sufficient to separate two targets of equal signal strength 5 degrees apart. This was confirmed experimentally.

Although the field trials of the 692 sonar were of a limited nature, sufficient data were obtained to confirm the above statements on performance. No trials were made of the short-pulse echo-ranging equipment except to check its operation. It is expected that further trials will be made by the Navy to obtain additional information on the capabilities of the system as a whole.

11.2 DESCRIPTION OF EQUIPMENT

The four major components of the 692 sonar are the projector, the projector training system, the listening stack, and the short-pulse echo-ranging stack. The listening system is itself composed of a number of units, each of which is described separately. A block diagram of the listening system is shown in Figure 2.

11.2.1 Projector

The design requirements called for a projector to cover the range from 200 c to 60 kc for listening and from 10 to 60 kc for echo ranging. Also, the unit should not be more than 36 inches high and should be in a cylindrical case not more than 13 inches in diameter. As 13-inch tubing was not commercially available, the latter requirement was revised to 14 inches. A requirement that the unit be capable of withstanding gun blast and a static pressure of at least 400 psi was also specified.

By specifying both size and frequency range, the more important characteristics of the projector, including its directivity, were defined. It was agreed that the requirement could best be met at the time by employing a three-section projector; one section to cover the l-f range from 200 c to 15 kc; a section consisting of a modified QBF projector to cover the intermediate frequencies from 15 to 30 kc; and a h-f crystal plate of the same width but half the height of the QBF plate to cover the range from 30 to 60 kc. The l-f unit consists of a line of four diaphragm-type hydrophones, each containing a single block of crystals of the type used in the QBF plate. These four units are mounted between the h-f and i-f sections. The h-f unit is mounted at the top in order to minimize diffraction about obstacles on the deck of the submarine. The installed projector is shown in Figure 3.

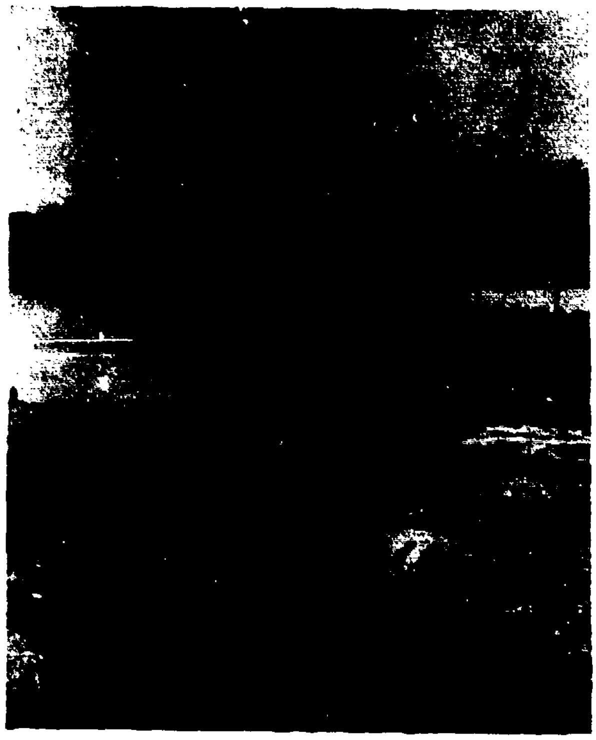


FIGURE 3. The 692 submarine sonar projector mounted on the deck of a submarine.

The h-f unit was made the same width as the other units in order to obtain maximum horizontal directivity. However, its height was made only one-half the width, so that the vertical directivity pattern would not be too sharp. Too narrow a beam in the vertical plane would unduly restrict the area from which signals could be received. Although none of the units in the 22Z-1 projector was tapered in the hori-

zontal plane, both the h-f and i-f units were tapered in the vertical plane to reduce the effect of reverberation.

In addition to meeting the Navy requirements, the design was aimed at keeping the absolute efficiency as high as possible over the listening range, thereby keeping the thermal noise low with respect to ambient water noise. This is particularly important at the higher frequencies. An effort was also made to keep the phase shift between the halves of the projector to a minimum in order to provide good balance for the phase-sensitive detector.

Crystal Arrays

The arrays are mounted on a steel frame which bolts to the housing. Front and back views of this assembly are shown in Figures 4 and 5. The h-f array is at the bottom of the photograph, the sonic or l-f array is in the center and the i-f array from 10 to 30 kc is at the top. When mounted topside on a submarine, this order is reversed and the i-f array is at the bottom.

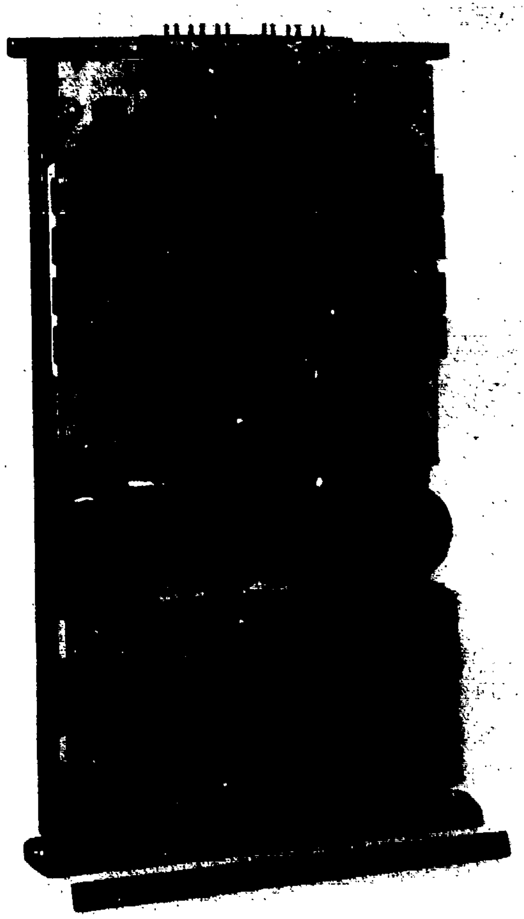


Figure 4. Front view of crystal arrays in the 692 projector.

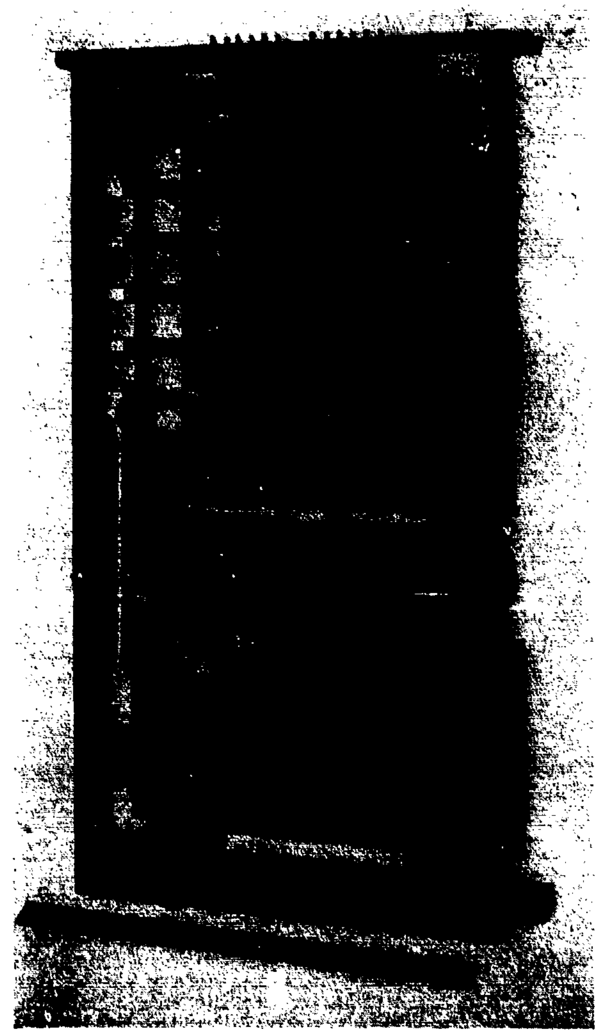


Figure 5. Rear view of crystal arrays in the 692 projector.

As shown in Figure 5, the h-f and i-f arrays are supported at the four corners by brackets which are mounted in a shock-insulating type of rubber support developed for the QBF projector. The l-f array is similarly shock-mounted to a cross member of the frame. The frame also supports terminal strips, a wiring form, repeating coils for the h-f and l-f arrays and

protective neon lamps. These are not shown in the photographs.

Projector Characteristics

The characteristics of the projector to a large extent determine the capabilities of any sonar system. No refinement of the electric circuit can make up for deficiencies in the projector, particularly as regards its internal noise threshold and its directivity. Frequency response is not basically important but may be used to calibrate the output in various listening bands in terms of sound pressure in the water.

Frequency Response. The open-circuit calibration of the projector used as a hydrophone is shown in Figure 6. This type of measurement is significant from a design standpoint. It shows a high peak at the cutoff frequency of the transformer which is compensated for in the amplifier input transformer.

The calibration of the h-f and i-f sections of the projector when used to transmit sound into the water are shown in Figure 7. The h-f unit is somewhat more efficient in this respect, due primarily to a better directivity index.

Internal Noise. The internal noise spectra for the projector are shown in Figure 8. The l-f unit is poorest in this respect. A higher level of internal noise can be tolerated at the low frequency because the spectrum of ambient and self-noise rises toward the low end. Furthermore, the directivity becomes less and thus a

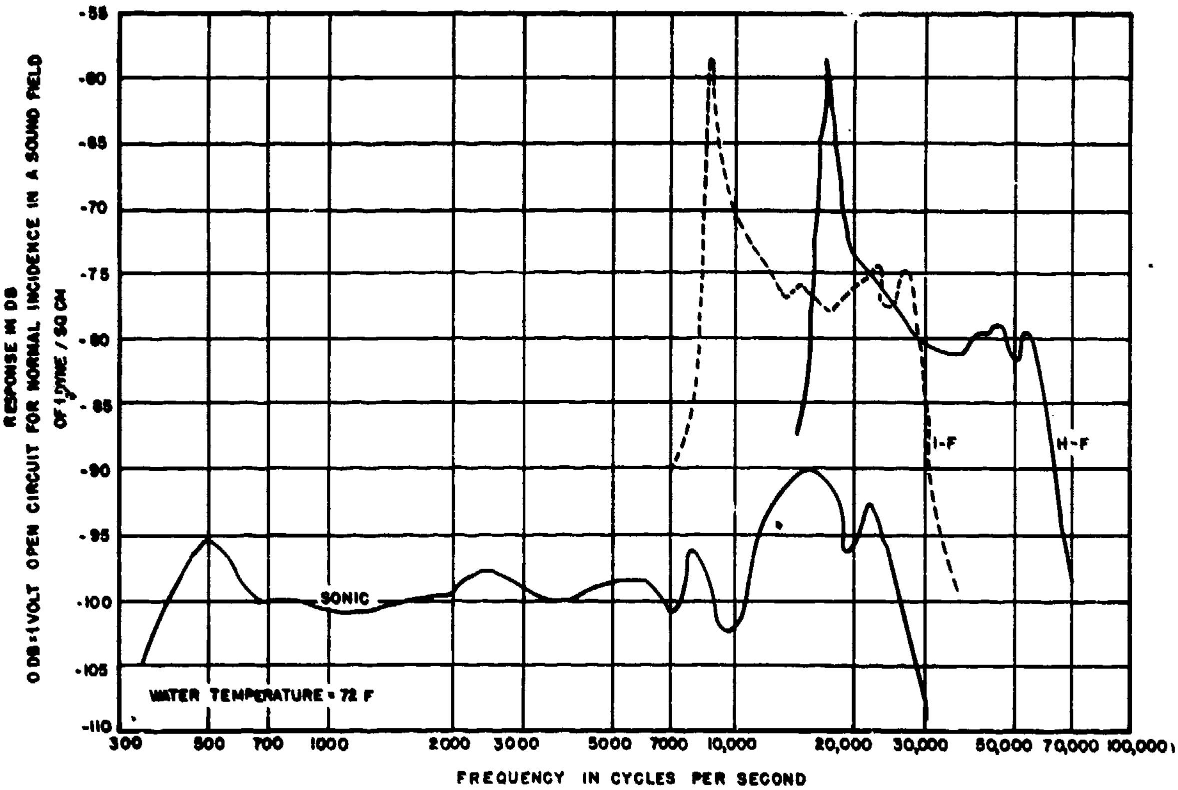


FIGURE 6. Open circuit calibration of WFA No. 22-Z projector used as a hydrophone.

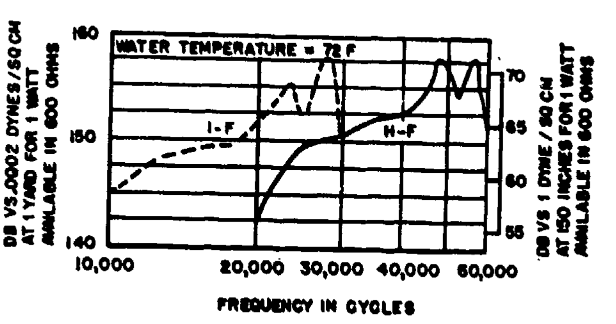


FIGURE 7. Calibration of h-f and i-f sections of WFA No. 22-Z projector.

higher level of ambient noise is accepted. However the l-f unit is limited by internal noise wherever low ambient and self-noise levels prevail.

and 36 kc are given in Figures 9B, 9C, 9D, 9E, and 9F, respectively. With the exception of the pattern for 36 kc, these curves show increase in directivity with frequency, which is in agree-

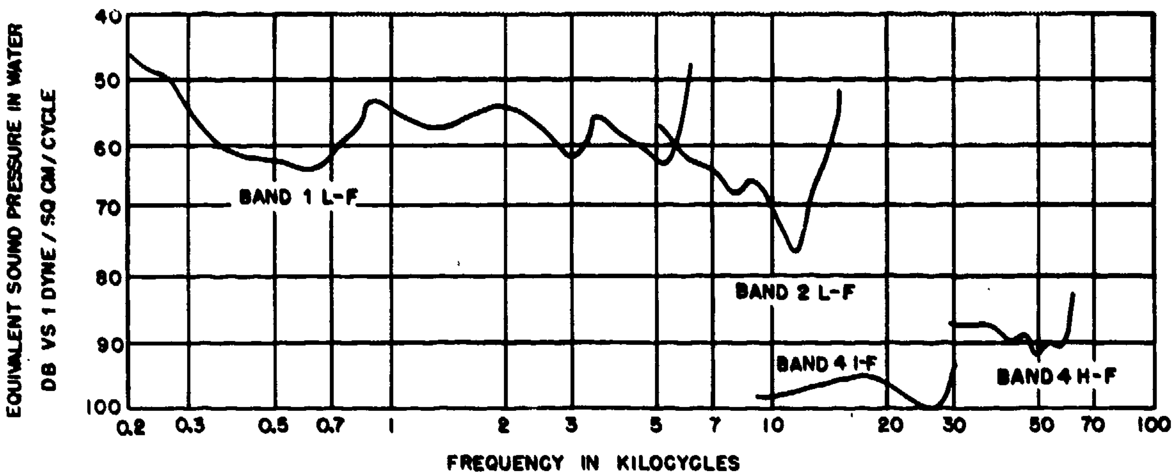


FIGURE 8. Internal noise spectra of WFA No. 22-Z projector used in the 692 submarine sonar.

Directivity The calculated directivity patterns for the i-f array at 24.5 kc in both the horizontal and vertical planes are shown in Figure 9A. These patterns show the effect of the taper, which reduces the side lobes at the expense of the main lobe, which becomes larger. The patterns also show that the directivity of the individual blocks has a slight effect on the side lobes.

An array with taper in the horizontal plane is considered desirable from an echo-ranging standpoint, as the reduced side lobes minimize the possibility of errors due to false echoes. However, when listening with a *phase actuated locator* [PAL], such an array is not so desirable from an interference standpoint as a linear array. This is shown by the curves in Figure 10, where the bearing error in degrees is plotted against angular separation between the target and an interfering signal of equal intensity for both tapered and linear arrays. It can be seen that the bearing error when using a tapered array is greater than that for a linear array when the angular separation between target and interference is between 9.5 and 17.5 degrees.

The measured directivity patterns of the i-f array in the horizontal plane at 12, 18, 24, 30, ment with the computed variation of directivity index shown with frequency in Figure 11. The measured pattern at 24 kc, Figure 9D, compares favorably with the calculated pattern in Figure 9A for 24.5 kc. The pattern at 36 kc is typical of what happens to the directivity outside the useful range where the response falls off and the phase conditions over the face of the projector begin to vary.

The calculated horizontal and vertical directivity patterns at 49 kc for the h-f array are shown in Figure 12A. The measured horizontal directivity patterns for this array at 30, 40, 50, 60, and 80 kc are shown in Figures 12B, 12C, 12D, 12E, and 12F.

The l-f array in the 22Z-1 projector has relatively low directivity, due to dimensional restrictions. It is essentially nondirective in a vertical plane and its measured directivity in a horizontal plane for 2.2, 6, 9, and 15 kc is shown in Figure 13. It will be observed that at 2.2 kc there is practically no directivity and at 15 kc there is only moderate directivity. Because of its poor directivity, this array is used for listening only and no attempt is made to use the PAL with it because of the inability to distinguish among sound sources.

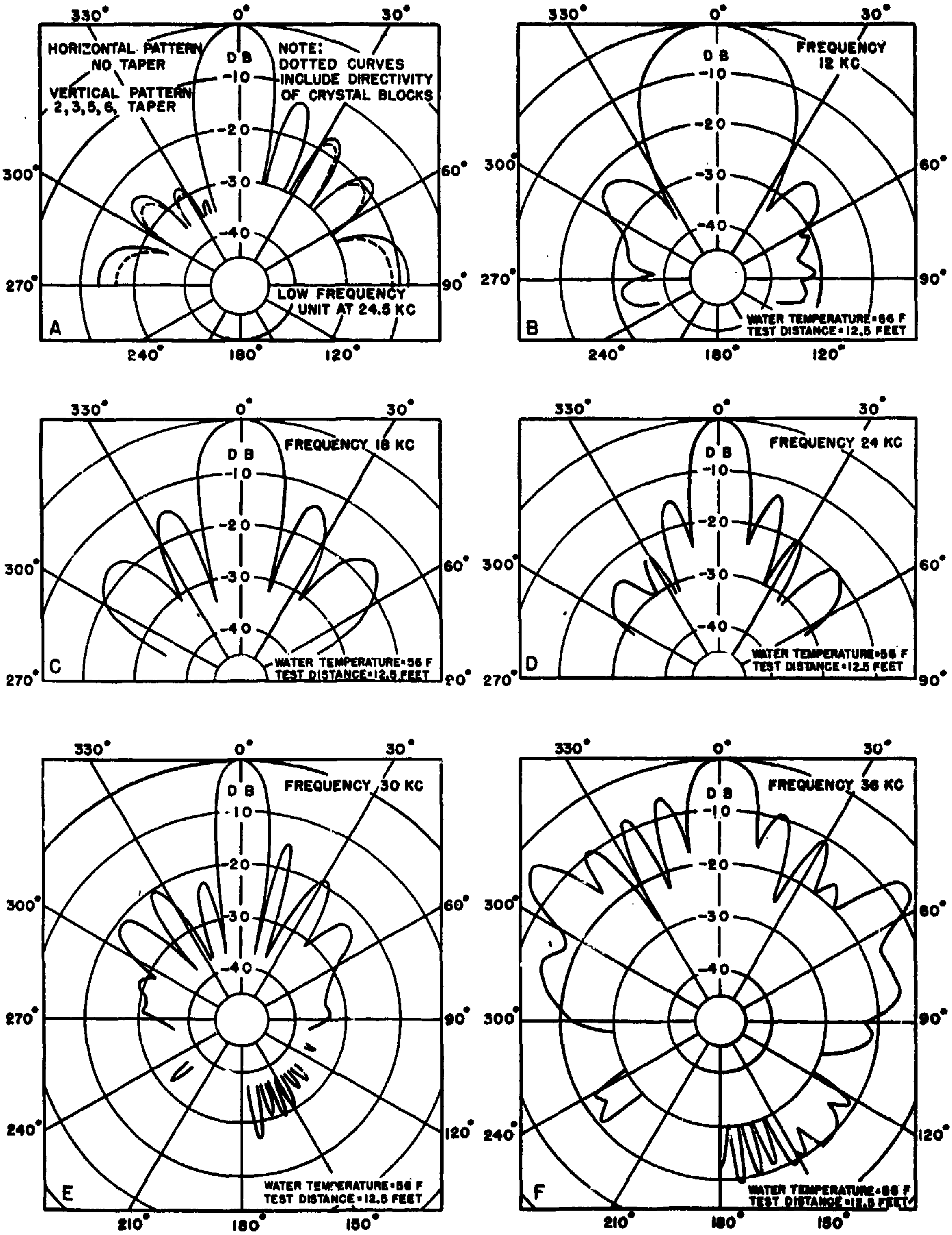


FIGURE 9. Directivity patterns for i-f unit of WFA No. 22-Z: (A) Calculated vertical and horizontal patterns at 24.5 kc in db down from maximum response; (B)—(F) Measured horizontal patterns at several frequencies, in db down from maximum response.

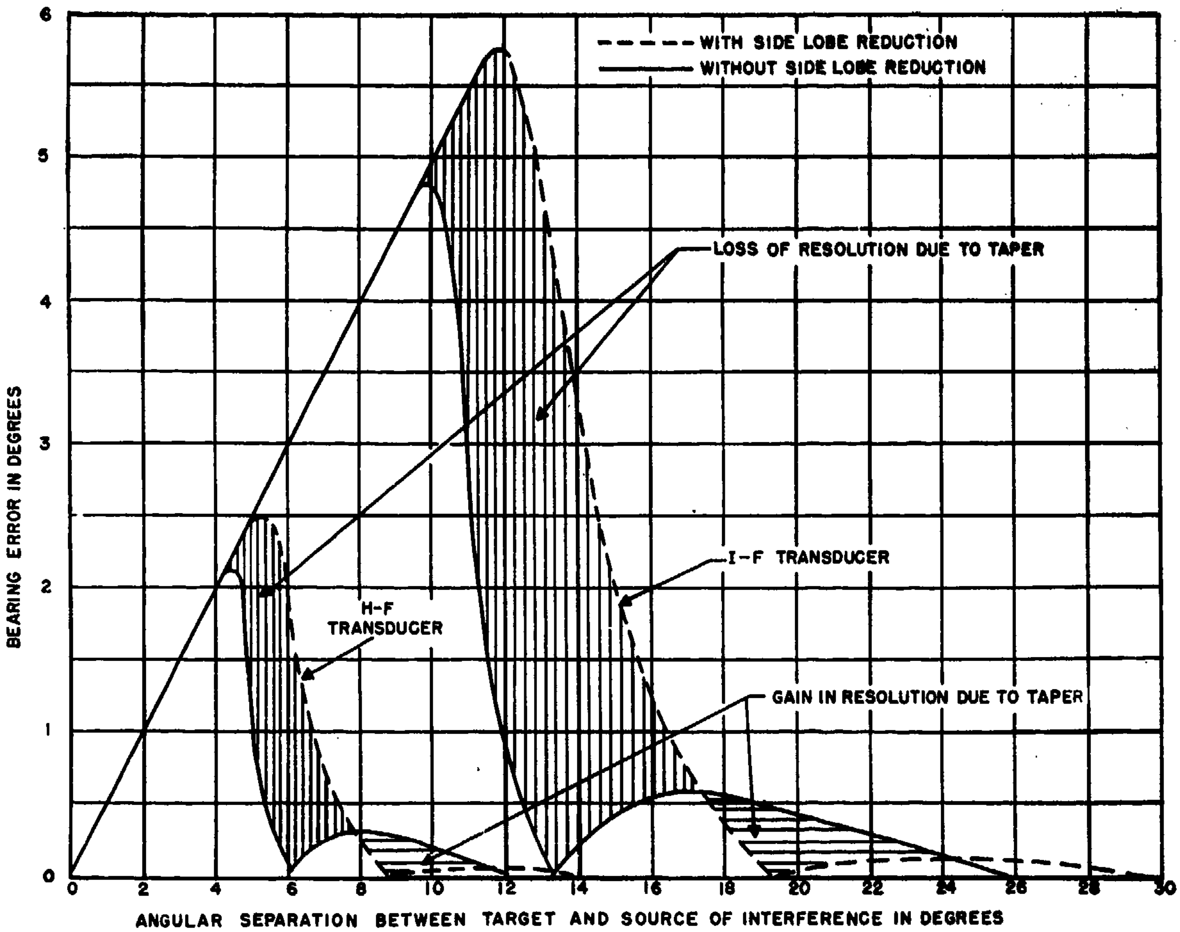


FIGURE 10. Error of phase-actuated target bearing indication caused by an interfering signal of equal intensity.

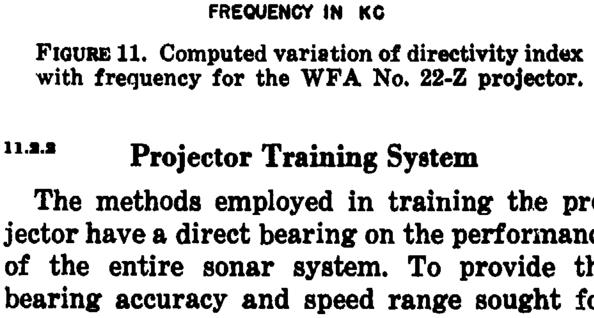


FIGURE 11. Computed variation of directivity index with frequency for the WFA No. 22-Z projector.

11.2.2 Projector Training System

The methods employed in training the projector have a direct bearing on the performance of the entire sonar system. To provide the bearing accuracy and speed range sought for in this training system, it was necessary to employ methods other than those used in existing sonar systems to meet the more stringent requirements discussed below.

PERFORMANCE REQUIREMENTS

Several requirements were initially emphasized. First it was considered desirable to be able to align positively the acoustic axis of the projector within ± 0.1 degree of any bearing desired. For following targets, a smooth continuous shaft speed range adjustment was sought from about 0.1 degree per second for slow ships at long ranges to about 4 degrees per second for fast ships at close ranges. Higher shaft speeds up to about 30 degrees per second were considered necessary for slewing quickly from one bearing position to another and a single high speed of about 360 degrees per second was needed for continuous search. This wide range of shaft speed had to be ac-

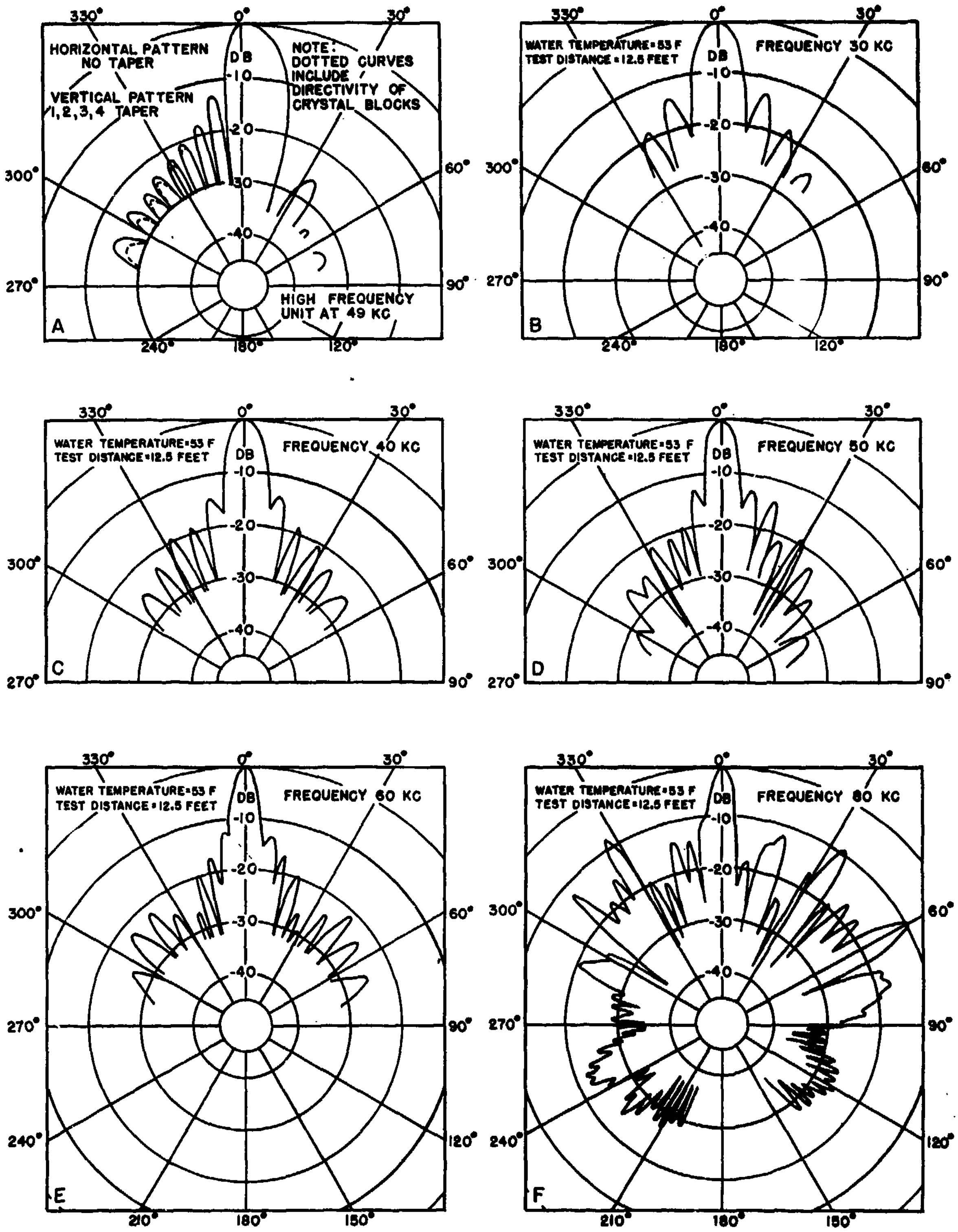


FIGURE 12. Directivity patterns for h-f unit of WFA No. 22-Z: (A) Calculated vertical and horizontal patterns at 49 kc; (B)—(F) Measured horizontal patterns at several frequencies.

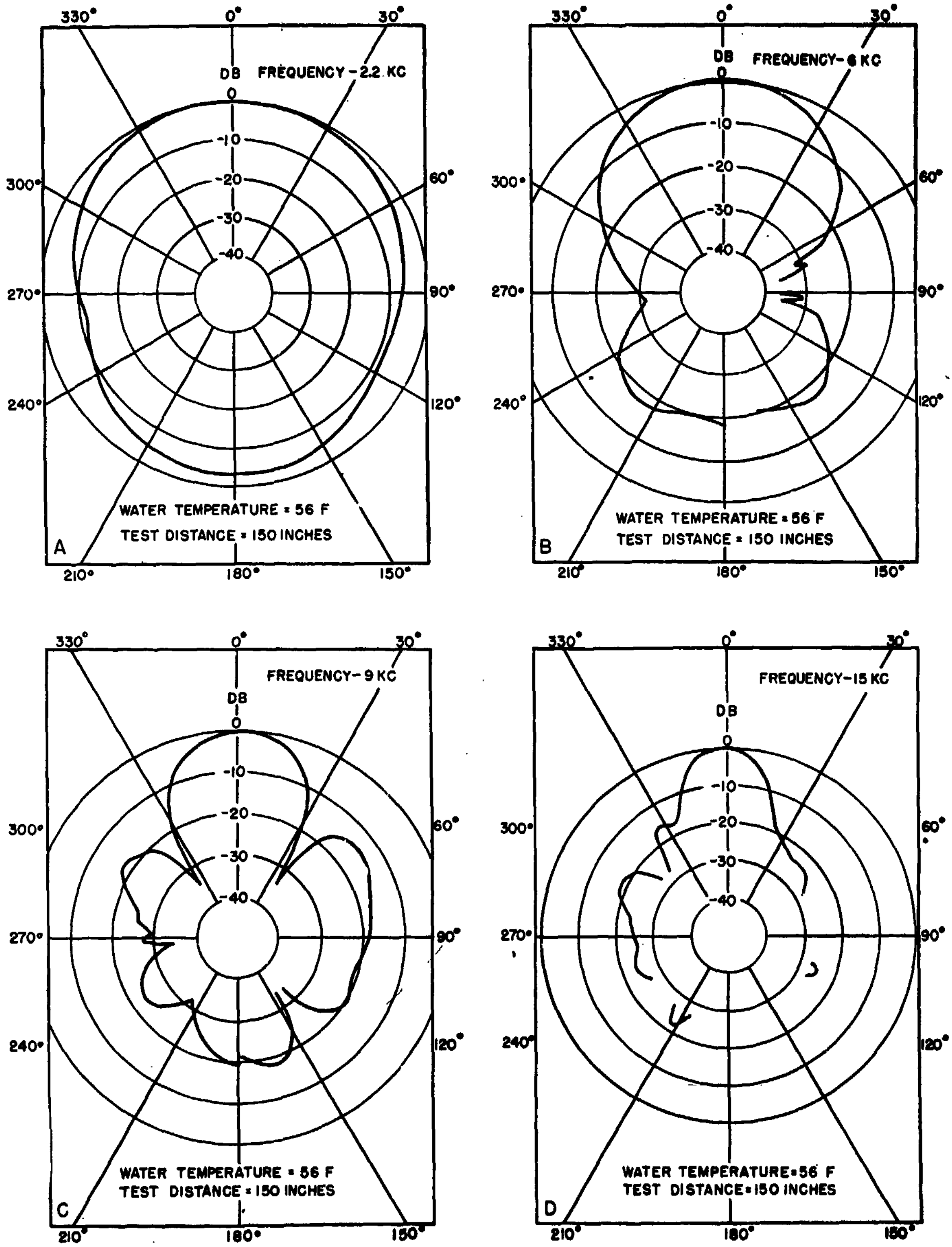


FIGURE 13. Measured directivity patterns for l-f unit of WFA No. 22-Z in the horizontal plane at several frequencies.

complished without discontinuity, except between the slewing and search speeds, by a mechanism that could be controlled from a remote position and which would neither introduce noise into the listening system nor radiate sufficient sound into the water to endanger the security of the ship. The noise problem was considered of prime importance and much attention was given to design features that would be expected to reduce the mechanical vibration transmitted to the training shaft or to the ship's hull. Another characteristic of the training system that it was necessary to consider at the outset was its adaptability to some form of automatic target tracking arrangement.

Speed Control System

After considering many possible arrangements to cover the wide speed range, including systems with two or three motors, magnetic and indexing clutches for selecting different gear ratios, mechanisms outside the hull sealed in oil, and differential and planetary gear systems, there was evolved a drive system of attractive mechanical simplicity operating through the hull with one motor. This design was made possible by a wide-range motor speed control system using mercury contact relays.

Training Mechanism

In order to couple the motor to the training shaft, it was necessary to design and build a mechanism assembly with a suitable speed-reducing gear and to provide a take-off drive for the coarse and fine synchro generators used for remote bearing indication. The problems involved were unusual because of the high accuracy of training sought, the wide range of speed required, the probability of bearing and gear noise, particularly at the search speed, and the necessity of avoiding resonances and excessive displacements in the supporting members. Flexible supports are necessary to isolate the training shaft from undesirable vibrations but excessive displacements in these suspensions would affect the positional accuracy of the training mechanism. Furthermore, the suspensions and shaft couplings are important elements in the feedback loop of any automatic target tracking system working through the mechanism, therefore they were designed with mechanical impedance characteristics to keep to a minimum any phase or amplitude effects at frequencies below 10 or 15 c.

The gear system for coupling the drive motor to the training shaft required features that were not obtainable in commercial gear boxes. The training accuracy desired for the system required that backlash and run-out errors in the gears be less than 0.1 degree, which is better than could be assured by any commercial supplier. Also, it was particularly important that gear noise be very low.

The gear system designed and built consists of two worm gears mounted on a hub through which the training shaft can be passed. The worm shaft is carried by ball bearings in an eccentric bushing to permit a close and precise adjustment of the mesh between the worm and gear. Both worm gears and their mating gears were specially cut to order with the highest precision equipment available, and the whole gear system is enclosed in an oil-filled housing.

To attenuate any residual gear and bearing noise that might be transmitted to the training shaft, a special, flexible coupling was designed for use between the gear hub and the training shaft. This type of coupling introduces a high compliance to all translational forces between the gear box and the training shaft and thereby attenuates noise vibrations having translational motions. However for torsional motions this coupling is very rigid. Measurements were made which showed the torsional displacement to be considerably less than 0.1 degree when transmitting a full load torque of about 30 foot-pounds.

The drive motor is, in reality, two separate motors in one housing, as may be seen in the schematic diagram, Figure 14. These have two separate dipole fields with their pole axes at 90 degrees to reduce intercoupling and two separate armatures and commutators, one for low-speed operation and the other for high-speed operation or back emf generation. Both armatures have winding slots spiraled by one slot in pitch to reduce cogging. The brushes and holding frame were designed to give quiet oper-

ation and good commutation for either direction of armature rotation.

11.2.3 Listening System

The listening equipment in the 692 sonar covers a broad frequency range with means for selecting bands of different widths anywhere in the range. A block schematic of the system is shown in Figure 2. This also shows the training controls which form part of the listening stack. The various panels, as well as their components, are blocked off.

The l-f unit of the projector, which is not involved in echo ranging, is carried through the slip rings and junction box directly to its own preamplifier in the measuring panel. Contacts on the band selector switch on this panel, when set on band 1, carry the output of the amplifier directly to a 5-kc low-pass filter and thence to the listening amplifier. When the selector switch is on band 2 the output of the preamplifier is taken to a modulator where it is put on a 190-kc carrier. From there it passes through a filter which selects a 10-kc band around 200 kc. This is heterodyned at 200 kc in the demodulator, resulting in a folded band where 200 kc becomes zero frequency and both 195 and 205 kc become 5 kc. This is then passed through the 5-kc low-pass filter and on to the listening amplifier.

The i-f and h-f units pass through a selector switch on the control panel. From there each half of the projector goes through its own preamplifier and then through a mixer circuit which leaves the sum on the right channel and the difference on the left channel. These are amplified in accordance with the setting of the gain control. The outputs then go to the modulator panel, where both the sum and difference are put on a carrier whose frequency is selected by the mid-band dial marked from 10 to 60 kc. This dial actually controls a variable oscillator working between 145 kc and 191 kc. For instance, if a 4-kc band from 10 to 14 kc is desired, the mid-band dial is set at 12 kc, the signal from the i-f projector would then modulate 191 kc, resulting in a sum output from 201 to 205 kc. Similarly, if it were desired to use 56 to 60 kc, the mid-band would be set at 58 kc, which corresponds to 145 kc, again resulting in an output from 201 to 205 kc. The output from the sum channel is tapped before it reaches the 4-kc wide filter and brought up to the sound level panel where it is available for band 3. This is similar to band 2 and makes available a 10-kc folded band from the i-f and h-f units.

The output also passes through a 4-kc wide filter to the demodulator where it is heterodyned at 200 kc. At this point a 90-degree phase shift is introduced between the sum and

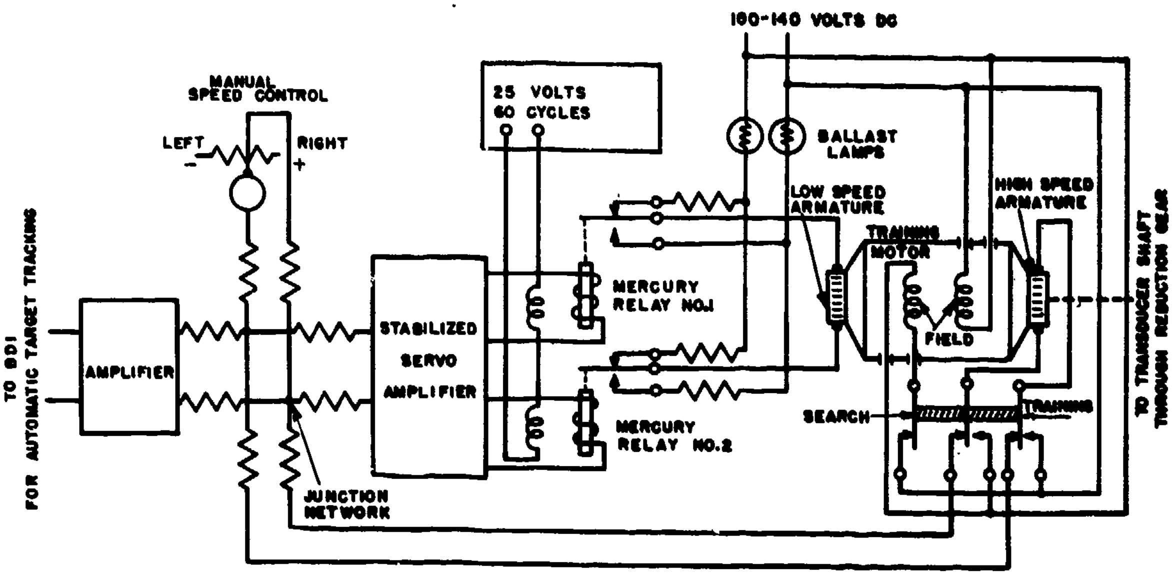


FIGURE 14. Schematic of training control circuit, 692 submarine sonar.

difference channels. The demodulated output of the sum channel, which consists of a band from 1 to 5 kc, is fed directly to the listening amplifier. The same band, together with the corresponding one from the difference channel, goes to a phase-sensitive detector.

A novel use is made of the voltages which operate to control the volume in the detector automatically. Since these voltages follow the levels in the two channels, their combination forms a sum which is more sensitive to phase than the direct combination of the two halves of the projector which is used for listening. This output furnishes the signal to control indicator lights on continuous search. The normal output of the phase-sensitive detector which is zero for the projector "on bearing" is used to operate the meter associated with the vernier scale in the indicator panel. It is also fed to a d-c amplifier in the detector panel and thence through the MTB panel, the AUTO switch and servoamplifier on the control panel, and from there to the motor control unit. This is a servo loop whereby the projector output generates a voltage proportional to the angle the projector makes with the target, and this voltage is fed back to the training motor which rotates the projector until it is on bearing and no longer generates the voltage.

The MTB panel serves as a junction for the output of the d-c amplifier in the detector and the input to the servoamplifier. However, the MTB circuit may be switched to this input in order to control the bearing of the projector. Even when not controlling, it shows the true bearing of the projector by combining the information received from the synchro generator at the projector shaft with that from the ship's gyro compass.

The listening equipment is housed in a stack, shown in Figure 15, consisting of six cabinets. The complete assembly weighs about 1,000 pounds. In order to reduce the weight, the cabinets and panels were made of suitable aluminum alloys. When mounted on shipboard, the cabinets are bolted together and are fastened at the top and bottom through rubber shock mountings.

The stack is arranged so that the indicator panel is somewhat below the average eye level when the operator is standing and is somewhat above when sitting. The controls are grouped on the top four panels within reach of an operator either standing or sitting. Each cabinet is described in detail in the following sections.

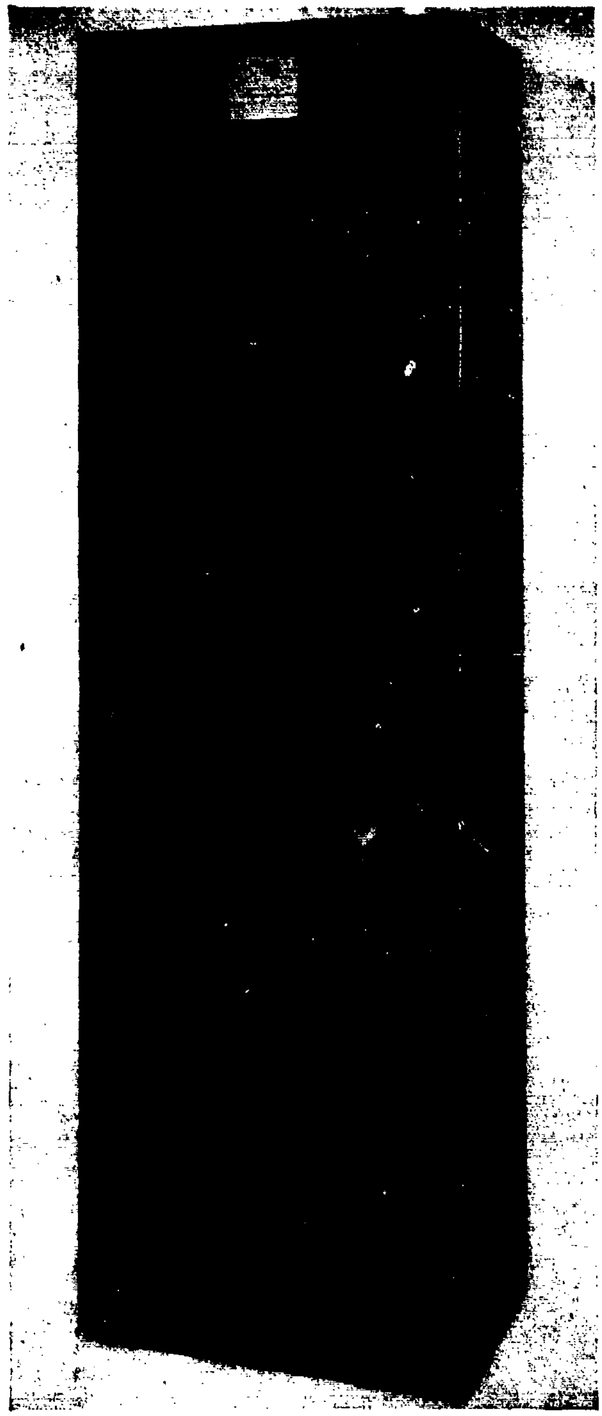


FIGURE 15. Stack housing listening equipment, 692 submarine sonar.

Sound Level Panel

The topmost cabinet of the listening stack contains the audio listening amplifiers and a sound level indicator. It also contains some modulators, an alarm generator, and a loudspeaker. As shown in Figure 16, the level meter

Figure 16. Close-up of top cabinet of listening stack, showing sound level meter.

appears at the upper left. The listening inputs are controlled by the left-hand dial. The first two steps connect the l-f array to the listening system. The first step takes the output of the l-f preamplifier directly through a 5-kc low-pass filter and thence to the loudspeaker or headphones through the listening amplifier. The second step takes it to a modulator in such a way that the 5-kc bands either side of 10 kc are superimposed and stepped down to the range below 5 kc before passing through the filter. The third step does the same for a 10-kc band centered at 3 kc below the mid-band frequency selected on the modulator panel. In this case either the h-f or i-f element of the projector is connected to the system, as determined by a switch on the control panel described later.

Indicator Panel

The indicator panel shown in Figure 17 furnishes the bearing information obtained from the listening equipment. The outer azimuth circle is for relative bearings. Just within this is a ring of diamond-shaped light apertures. A white pointer travels within this circle to indicate the position of the projector. There then follows a compass card which is connected through a servomechanism to the ship's gyro compass and shows the true bearing. The *bearing deviation indicator* [BDI] and the vernier relative-bearing dial appear in an opening cut in the central mask.

As the projector is rotated, the white pointer rotates with it. When the projector is brought to bear on a target the position of pointer on the outer circle indicates the relative bearing of the target with an accuracy of a few degrees. The BDI meter needle swings from side to side as the projector passes through the target and is at dead center when the projector is exactly on bearing. The exact bearing can then be read from the small dial to the nearest tenth of a degree. For instance, the target bearing indicated on the photograph is 343.2 degrees. If it is desired to know the true bearing, this can be read to the nearest degree on the compass card. There is no relation between this and the small dial. When the listening equipment is switched over to continuous search, a light

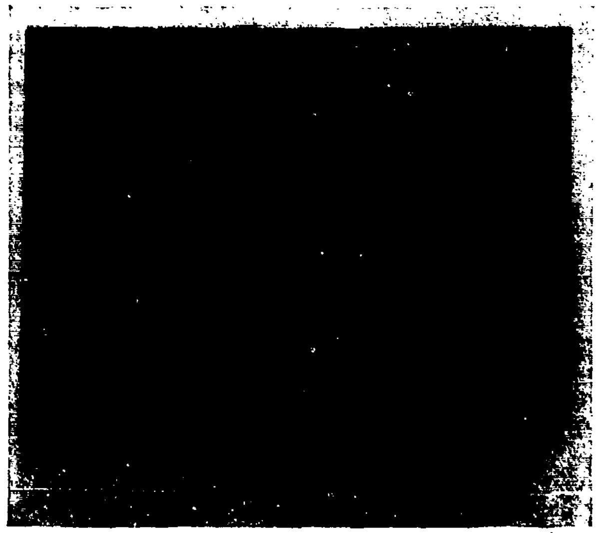


Figure 17. Close-up of second cabinet of listening stack, showing indicator panel.

flashes at the bearing of a target and there is sufficient delay in the circuit to keep the light lit between revolutions as long as the target is within sound range.

The upper left-hand dial controls the intensity of the dial lighting. The large plastic dial face is of a color designed to pass those rays in the red portion of the spectrum (greater than 6,000 Angstroms) which have

been found to have the least effect on night vision. The upper right-hand dial is used to synchronize the servomotor driving the compass card with the ship's gyro. This is required only when the ship's compass system is of the step-by-step type.

The lower left-hand dial controls the sensitivity of the BDI meter. This is optional with the operator, depending on how much meter swing he prefers when passing through a target. The lower right-hand dial controls the intensity of the flashing lamps.

Modulator Panel

The modulator panel shown in Figure 18 is arranged to select the mid-band frequency for either the h-f or i-f projector units. The center dial drives the condenser plates of a variable oscillator and displays the mid-band frequency for the i-f unit on the left and for the h-f unit on the right. The lower dial switches

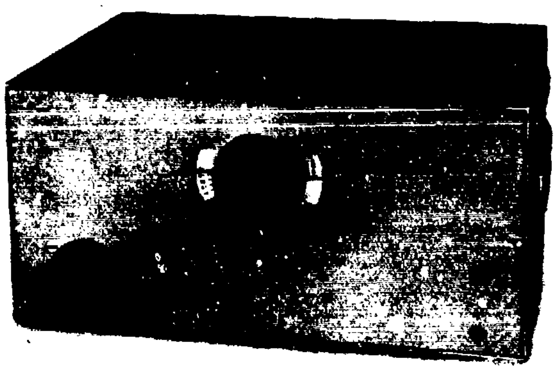


Figure 18. Close-up of third cabinet of listening stack, the modulator panel, showing frequency selector dial.

from a 4-kc bandwidth to the full bandwidth of either the h-f or i-f units. The full bandwidth feature was included to provide a means for detecting, on continuous search, enemy echo ranging which might appear anywhere in the band and would be difficult to locate with a narrow-band listening system.

Control Panel

The i-f and h-f sections of the projector are directly connected to the control panel shown in Figure 19 and are selected by means of the upper left-hand dial. This panel contains the initial amplification for these elements, also the mixers to obtain the sum and difference channels for the BDI, the initial gain control,

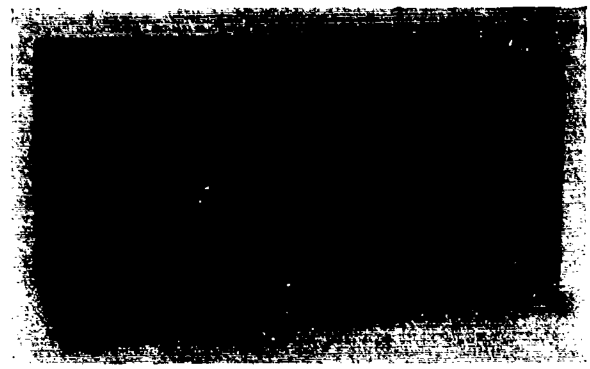


Figure 19. Control, or fourth, cabinet of listening stack.

an additional 35 db of amplification in each channel, and the training control servoamplifier. The handwheel may be turned either to the left or right within a 180-degree arc, the excursion determining the speed in that direction at which the projector rotates. In other words, for a very small change of bearing, the wheel is turned a very small amount to provide a slow training rate in the desired direction. The action of the projector is of course shown by the pointer on the indicator panel.

Under the handwheel is a switch for selecting one of three conditions: continuous search listening [CSL], hand training, and automatic tracking. The operator can locate a target by hand operation of the wheel and immediately switch over to automatic tracking, whereupon the projector stays on the target without requiring any further manual operation. If no targets are within sound range, he may wish to set the projector in motion by switching to CSL, whereupon it continues to rotate and flashes one or more lights at the bearing of a target when it comes within range. The center dial marked "level" controls the gain of the panel in 5-db steps.

Detector Panel

The detector panel shown in Figure 20 amplifies the sum and difference outputs of the modulator panel, using either a 4-kc band re-

duced to the audible range or the full band of the i-f and h-f projector units. The phase difference between the two channels using a

FIGURE 20. Detector, or next-to-bottom, cabinet of listening stack.

4-kc band provides the BDI indication of bearing. The circuit also provides the equivalent of a phase-sensitive maximum output which, when amplified and limited, provides the signal to flash the proper lamp on continuous search. The BDI voltage is applied to the meter and is also amplified and limited to furnish a control voltage which is fed back to the d-c servoamplifier for automatic tracking. A test tone generator for adjusting the BDI is also mounted on this panel. The ADJ zero dial is used to center the meter during the test operation.

POWER SUPPLY PANEL

This panel contains two regulated plate supplies, each of nominal 300 volts. The load has been divided between them in such a way as to avoid noise troubles. The combined return is used to heat the cathodes of four tubes in critical portions of the listening system circuit. Pin jacks are mounted on the panel for connecting a voltmeter to check each supply.

MAINTENANCE OF TRUE BEARING [MTB] PANEL

This panel, shown in Figure 21, contains synchro units connected with the projector training mechanism and with the ship's gyro compass. They drive dials to indicate both the ship's and the projector's true bearings. They are also arranged to furnish a signal which can be fed through a detector system to actuate the projector motor drive in such a way as to maintain the projector on whatever true bearing appears on the dial. This is analogous to the automatic tracking feature. In this case the ship's gyro keeps the projector on a preselected true bearing.

The large knob at the left is used to synchronize with the ship's master gyro compass when the equipment is first set up. From then on, the left-hand dial reads the same as the ship's compass and gives the true course of the ship. The right-hand dial shows the true bearing of the axis of the projector at all target-following training speeds. The lower right-hand control switches the circuit from automatic target tracking to maintenance of true bearing. When switched to the latter, the projector automatically maintains itself at whatever true bearing

FIGURE 21. Maintenance-of-true-bearing [MTB] cabinet used with listening equipment.

appears on the right-hand dial. In this condition the dial may be turned to change the true bearing if desired.

11.3 PERFORMANCE AND CONCLUSIONS

The 692 submarine sonar, as an experimental system, has been found of value in determining the feasibility of features considered as requirements for the ultimate submarine sonar. In general, it can be considered that the 692 sonar has come through the development stage and is now ready for a Navy experimental program which will properly evaluate its capabilities. Some of the features, particularly those involving projector training and listening, have

been studied by engineers in the field. However, the short pulse echo-ranging and mine-detection equipment has not as yet been put aboard a ship.

The listening system covers a range from 200 c to 60 kc, and suitable listening bands can be selected on a continuous basis. The listening ranges are limited under most operating conditions only by the ratio of signal to ambient noise at the projector. Wide frequency range and low internal noise are also features of the WFA submarine sonar, which uses a somewhat similar projector.

Calculations indicate that an interfering sound source of equal intensity has no appreciable effect on the target bearing obtained by 692 sonar until the interference is within ± 12 degrees at the lower frequencies and ± 5 degrees at the higher frequencies. Limited tests indicate that such resolution can be obtained in practice.

The projector training system has been found to be quite satisfactory from a functional standpoint; its low self-noise level does not interfere with listening and is below ambient noise under most conditions. Combined with the use of a BDI, it permits reading target bearings to within 0.1 degree. The hand control is of the slewing type in that it varies the speed of train rather than having the projector follow a setting on the control. It was found quite satisfactory under the usual operating conditions. In this respect it is like steering a car where a given turn of the wheel produces a constant rate of change of direction, not a new direction, as would be obtained with a follow-up type of control.

Trials of the automatic target tracking feature under ideal conditions at a lake showed an average bearing lag error of 0.08 degree with a standard deviation of 0.08 degree. At sea, where such variables as water transmission conditions and actual sound target location are involved, the standard deviation of the sound bearings with respect to the stern of the target was about 0.15 degree. This means that for practical purposes sound bearings obtained by the 692 sonar are well within ± 0.5 degree of the actual relative bearing of the sound source. The test data contain errors inherent in the measuring means, so that the absolute accuracy of the system is probably better than indicated. The accuracy of the 692 sonar training system was such that similar training systems were used in a trial model of a triangulation ranging equipment.

The continuous search feature was found helpful for locating targets before switching to automatic target tracking. Experience indicated that this feature should also be of considerable aid during evasive tactics, as it displays the true and relative bearings of all attacking ships within sound range. The continuous search feature is also suitable for torpedo detection and tracking. However, considerably more data are required before its worth in this connection can be evaluated.

Although the listening system does not provide a direct observation of target range, it was found that by using the sound-level meter indication and by determining the frequency shift required to give a fixed loss in level, the target range could be estimated with reasonable accuracy.

Chapter 12

SUBMARINE TRIANGULATION-LISTENING-RANGING [TLR] SYSTEM

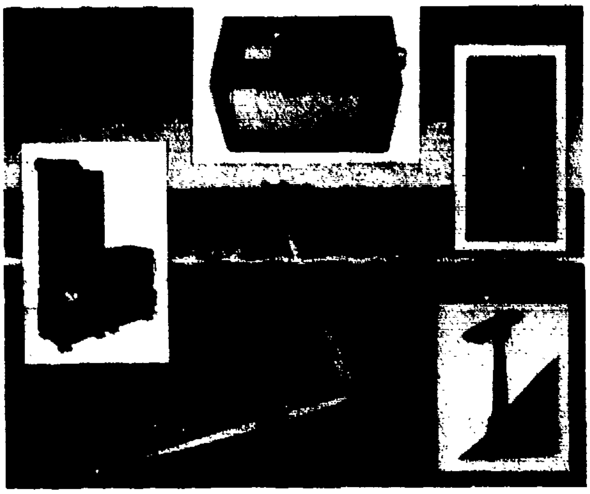


FIGURE 1. Components of the TLR system.

The submarine triangulation-listening-ranging [TLR] system, developed by CUDWR-NLL, is used to detect and determine the range and bearing of surface ships from a submerged submarine and indicate range on a recorder. The system includes two directional hydrophones mounted about 240 feet apart, right-left indicator [RLI] and listening equipment, automatic target follower [ATF] mechanisms, a triangle solver, and a chemical range recorder. The hydrophones are 5 feet long, straight, electrically split, magnetostriction units without lobe reduction. The RLI and listening equipments use the sum and difference signals from the two halves of each hydrophone to provide sonic listening, right-left indications, and actuation of the ATF mechanisms. The triangle solver makes use of the difference in target bearing from the two hydrophone stations to determine the target range.

12.1 INTRODUCTION

IN ORDER TO EXECUTE a successful torpedo attack, it is necessary for a submarine to have accurate information concerning the enemy vessel's course and speed. Determination of these two factors involves the use of bearing and range information ordinarily obtained by means of periscope or radar observations, with a final range check sometimes obtained by means of a single ping from the echo-ranging gear. An anticipated increase in the scope of enemy antisubmarine operations was expected, however, to increase greatly the danger of single-ping echo ranging and of radar mast or periscope exposure at ranges less than 3,000 yards.

Although accurate bearings can be obtained by sonic or supersonic listening methods, no means were available to obtain range information without the use of periscope, radar, or echo ranging observations. The necessity for discontinuing use of these methods of observation within 3,000 yards of the target would deprive the submarine's attack team of range information during the vital closing phase of an attack.

Preliminary investigations indicated that it might be possible to base such a ranging system on triangulation by listening, and a program was consequently undertaken.

This program led to the development of a *triangulation-listening-ranging* [TLR] system. It consists essentially of two listening stations a known distance apart aboard a submarine. Accurate target bearings from these stations can be translated into range by triangulation. The system is capable of determining ranges silently within about ± 10 per cent out to 3,000 yards for targets within ± 50 degrees of the beam. This accuracy is believed to be better than that usually obtainable by means of the periscope and is considerably better than the original seemingly difficult objective of ± 10 per cent accuracy at 1,000 yards range.

12.2 ANALYSIS OF THE PROBLEM

Prior to the start of development work, studies were made of the tactical requirements governing or limiting the use of triangulation systems and of the bearing accuracies required.

A triangulation system of the type under consideration is inherently most accurate when the target is on the beam of the submarine. As the target bearing approaches the bow or the stern, range accuracy decreases until the system becomes ineffective. A current study of submarine tactics revealed that the submariner is instructed to attempt to keep the target abeam as long as possible. Only near the end of an attack run just before firing or in certain special circumstances does the target bear close either to bow or to stern.

The range errors corresponding to bearing errors of various magnitudes for targets at several different relative bearings and ranges were determined both by calculations and by graphical means. From these determinations it was concluded[1] that, at a range of 1,000 yards, triangulation ranging might be anticipated to have a probable error of 12 per cent or less under the following conditions: (1) Standard deviation of bearing error must not exceed ± 0.25 degrees. (2) The system must be capable of taking bearing data rapidly enough to provide the number of readings necessary to obtain a reasonable average over a period of 5 to 10 seconds. (3) The relative bearing of the target from the submarine must lie within the limits 040 to 140 degrees or 220 to 320 degrees.

If accuracies better than ± 0.25 degree can be realized, the range accuracy increases accordingly and the usable arc is increased. When the target is directly on the beam, a range accuracy of 8 per cent may be anticipated at 1,000 yards for a bearing error (standard deviation) of ± 0.25 degree.

A discussion of these limitations with submarine commanders having recent patrol experience indicated that, while a usable arc of ± 50 degrees from either beam was considered acceptable, it was believed desirable, if possible, to reduce the anticipated bearing errors sufficiently to attain maximum probable range errors not greater than about 12 per cent at 2,000 yards (instead of at 1,000 yards) in order to provide range accuracies equal to or better than those obtained with the periscope.

In order to obtain bearings of the accuracy required for triangulation ranging, it was recognized as necessary to incorporate in the hydrophone system a means of providing for bearing deviation indication. Several BDI systems[a] had previously been developed for use in connection with other types of listening or echo ranging equipment and a comparison was made of four such systems,[b] each of which makes use of the difference in time of arrival (hence phase) of the incident sound at two hydrophone elements a small distance apart. On the basis of this study a BDI system designated as the *right-left indicator* [RLI], as described in Chapter 10, was selected as requiring the least amount of additional design and construction time and as having a possible inherent advantage in that the basic vector relationships are established in the input circuits.

12.3 DEVELOPMENT

Preliminary Surface Ship Tests

The fundamental elements of an experimental TLR system were first installed on a 127-foot long surface patrol ship. In this installation two hydrophones, consisting of straight, two-section magnetostriction units, were located 120 feet apart on shafts mounted overside from platforms constructed as far forward and aft as feasible. A power training system with an automatic target follower [ATF], and bearing repeater facilities was provided for each hydrophone. The RLI equipment, indicated in the block diagram, Figure 2, provided for operation in the band 5- to 9-kc and for wide-band listening from either channel.

The initial tests made with this equipment were directed toward determining the bearing accuracy obtainable with hydrophones from 3 to 6 feet in length. To facilitate comparison between bearings obtained sonically and the actual (or optical) bearing of a target vessel, an instrument known as a *direct deviation indicator* [DDI] was developed. The DDI consists essentially of a telescope mounted with the eyepiece directly above the hydrophone shaft center line and with its axis accurately lined up with the center line of the major lobe of the

[a] Discussed also in Division 6, Volume 15.

[b] The systems compared are designated as *simultaneous lobe comparison* [SLC], *phase-actuated locator* [PAL], *right-left indicator* [RLI], and the NRL system originated by the Naval Research Laboratory.[3]

hydrophone. The telescope covers a field of 4 degrees and is provided with a reticle having 0.1-degree divisions. The eyepiece of the telescope can be fitted with a 35-mm or 16-mm camera for photographing the target vessel to determine the deviation between optical and sonic bearings.

readings showed an accuracy of ± 0.21-degree standard deviation, while groups of 20 readings gave standard deviations of ± 0.06 degree to ± 0.14 degree. These data were obtained while tracking a tugboat presenting a beam aspect at 3,000 yards on a flat sea with no interfering targets. The results are summarized

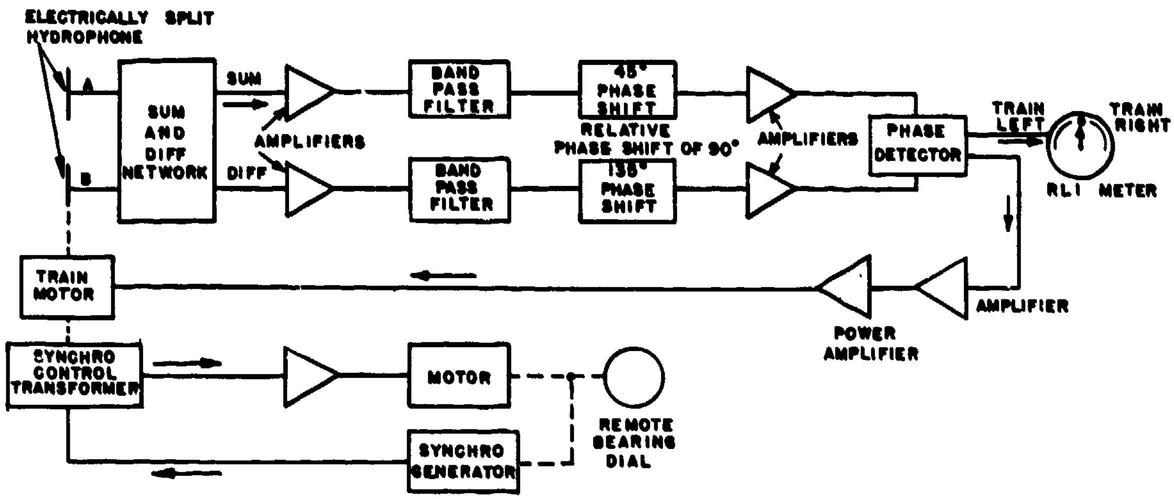


FIGURE 2. Block diagram of RLI system tested on surface ship.

Most of the surface ship bearing-accuracy tests were made with the vessel at anchor or drifting in a relatively calm sea. Various small craft served as targets, circling the listening ship at speeds of 6 to 10 knots and ranges of 300 to 2,000 yards. Occasional observations were also made on freighters or other traffic passing the operating area at ranges up to 5,000 yards.

Preliminary tests were made using a 6-foot, split JP-type hydrophone described in Chapter 10, an experimental RLI, and listening amplifier, and hand training at a 1-to-1 ratio. An analysis of four groups of observations, containing 35 to 352 readings, showed standard deviations of ± 0.47 degree with maximum deviations of 1.3 degrees from the correct bearing. Subsequent tests using 4-foot straight hydrophones and hand training through a 20-to-1 reduction gear gave a standard deviation of ± 0.55 degree for a group of 69 readings; and smaller groups of 15 successive readings resulted in standard deviations up to ± 0.62 degree.

After application of an ATF mechanism, 250 in the histogram, Figure 3. Bearing accuracies were determined with the DDI by analyzing exposures at half-second intervals. Numerous other motion pictures taken on calm days

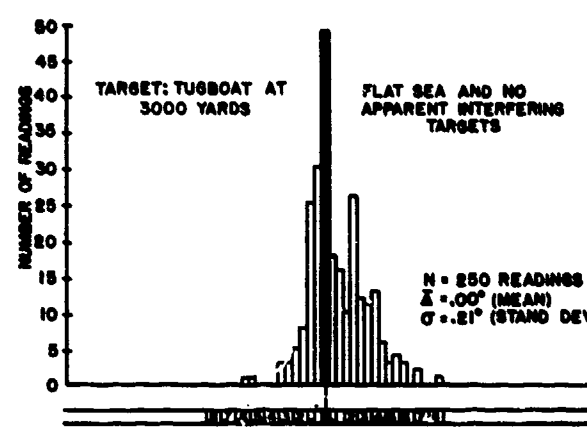


FIGURE 3. Histographic summary of surface ship bearing accuracy test.

showed that the bearing accuracies for 10-second periods, picked at random from a 5-minute period, were of the order of ± 0.15-

degree standard deviation when no interference was present.

Analysis of the results of these tests made it possible to define many of the factors affecting the accuracy of sound bearings measured with a system of this type and to estimate their probable effect upon ranges obtained by triangulation. Among these factors, the following appear to be the more important: (1) own ship's noise; (2) random water noises, directional distribution of which may not average out over short periods of time; (3) wake effects which may obscure the noise from the target's screws; (4) horizontal refraction due to currents of differing densities; (5) interfering targets; (6) the lag between the actual bearing of a moving target and the sound bearing; and (7) system errors.

The influence of some of these factors, such as wake effects and own ship's noise, were expected to be reduced when operating from a submerged submarine. The bearing errors caused by horizontal refraction and lag due to speed of the target are likely to be small and, since both hydrophones of a TLR system are equally affected, these effects would not be expected to introduce significant range errors. Interfering targets may cause bearing errors of considerable magnitude under certain conditions, particularly when the interfering signal is of comparable or greater intensity than that of the intended target and when the bearings of the two signals are close together.

The system errors which appear to be of most importance are: (1) lack of adequate matching in frequency sensitivity and phase characteristics of the two hydrophones and sum and difference networks, (2) mechanical backlash coupled with torsional and flexural strains in the hydrophone shafts which may cause the system to hunt, (3) bearing repeater errors due to inherent lag in the servo system, (4) overloading, from lack of adequate automatic gain control, which can cause false RLI and ATF deflections, and (5) the electric time constants in the RLI circuits which may cause hunting unless they are carefully chosen.

These preliminary surface ship tests indicated that, with a system having power training, RLI, ATF, and 4-foot split hydrophones, the original objective of bearing accuracies within ± 025-degree standard deviation could be realized for single targets and could probably be improved to about ± 0.15 degree by careful control of the system errors.

Preliminary Submarine Tests

It was apparent that similar tests should be conducted on a submarine to evaluate the effect of screw noise and hull vibration and to determine whether special methods would be required to permit ATF operation at speeds up to 3 knots.

A topside through-the-hull training gear was consequently installed for this purpose at a point a few feet forward of the screws on the submarine USS *S48*. In order to determine how much noise was transmitted to the hydrophone mechanically through the hull and how much was waterborne, a double hydrophone mount was used to allow the mounting of one hydrophone rigidly on the training shaft and another just above it on a vibration-isolating mount. Two 3-foot long split hydrophones mounted in JP-type baffles were used with an approximate 15-foot distance between the screws and the hydrophones.

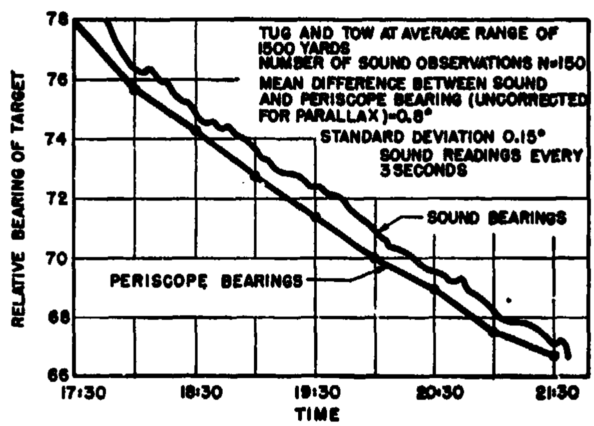


FIGURE 4. Comparison of sonic and periscope bearings for a typical run.

Initial listening tests, using RLI and power training equipment, indicated that at speeds of 3 knots and below screw noise was not serious with either the rigidly mounted hydrophone or the isolated unit. At speeds above 3 knots, cavitation was present and the noise level was high with both units. At all speeds, operation of the

stern planes caused noise that could be virtually eliminated by hand operation of the planes. The water noise at 3 knots and periscope depth was found to be low. Targets could usually be followed without difficulty to ranges of 4,000 to 7,000 yards from the submarine.

Bearing accuracy tests with this system showed average errors of ± 0.25-degree standard deviation. On one run, in which sound bearings were taken every 3 seconds on a tug at an average range of 1,500 yards, the standard deviation of bearing error, after corrections for parallax, was ± 0.15 degree. The results of this test are shown graphically in Figure 4.

12.4 EXPERIMENTAL SYSTEMS

USS *S48* Installation

A complete TLR system, incorporating a triangle solver mechanism and a range recorder, was built and installed for further testing on the USS *S48*. This system provided (1) minimum mechanical backlash in the hydrophone drives, (2) a bearing-repeat servo system accurate within about ± 0.03 degree, (3) an AVC system capable of stabilizing adequately the sound system in the presence of pulsating signals such as are usually generated by the screws of large ships, (4) an ATF, (5) continuous recording of ranges up to 4,000 yards on a moving chart and, (6) remote operation of the hydrophone system to allow control from one main station.

The design and construction of the triangle solver with its associated servo systems, the hydrophone drives, and the range recorder were assumed by the Sperry Gyroscope Company.

The equipment manufactured by Sperry for the *S48* installation [3] consists of dual Ward-Leonard hydrophone servo and drive systems, dual hydrophone bearing-repeat systems, and an associated triangle solver and range recorder, as indicated in the block diagram in Figure 5.

In this installation, the original aft training gear, having proved satisfactory in the earlier tests, was retained and a forward hydrophone installation was made between frames 22 and 23 to provide a base line of 205 feet between stations. The main control station was located in the motor room. A block schematic of the TLR system installed on this submarine, showing the forward hydrophone station and the components common to both stations, is presented in Figure 5.

Hydrophone Drives and Servo-Amplifiers. The servo system for each hydrophone incorporates an amplifier which feeds the field of a d-c generator whose output controls a d-c motor geared to the hydrophone shaft. Three methods of control are provided, search, hand, and ATF. In the search position, a potentiometer provides zero signal when in mid-position and provides smooth variation of the signal to give maximum training speed to right or left at the limit stops on the control. In the hand position, when the hydrophone bearing-repeat dials are moved by hand cranks from the actual hydrophone bearing, the error signal set up in the connected follower-synchro causes the hydrophone to rotate to the new bearing. In the ATF position, the output of the RLI sound stack is directly connected to the hydrophone servo-amplifier and causes the hydrophone to track the sound signal.

The Ward-Leonard system of hydrophone training control is well adapted to this application. The inclusion of a small permanent-magnet generator geared to the hydrophone shaft provides reverse feedback to the servo-amplifier, which allows large torque to take care of possible binding in the through-the-hull shaft and at the same time prevents excessive overrunning of the shaft and allows precise control of hydrophone training speed. The control by this system is extremely smooth and the sensitivity is excellent.

The bearing-repeat system consists of 1-to-1 and 36-to-1 synchro-generators connected to the hydrophone shaft, with similar control synchros on the bearing-repeat shafts geared directly to the triangle solver. A triangle solver servo-amplifier associated with each hydrophone bearing-repeat system provides repeated bearings accurate to a fraction of a tenth of a degree. Inverse-feedback generators and a smoothing circuit incorporated in the amplifier permit high sensitivity, freedom from hunting and sharp resonances, and considerable smooth-

ing of the fluctuations of the hydrophone when ATF is being employed. Bearings of the hydrophone shaft are repeated in this manner when ATF and search are used. For hand-controlled training, the dial bearings are repeated to the hydrophone shaft directly by the hydrophone

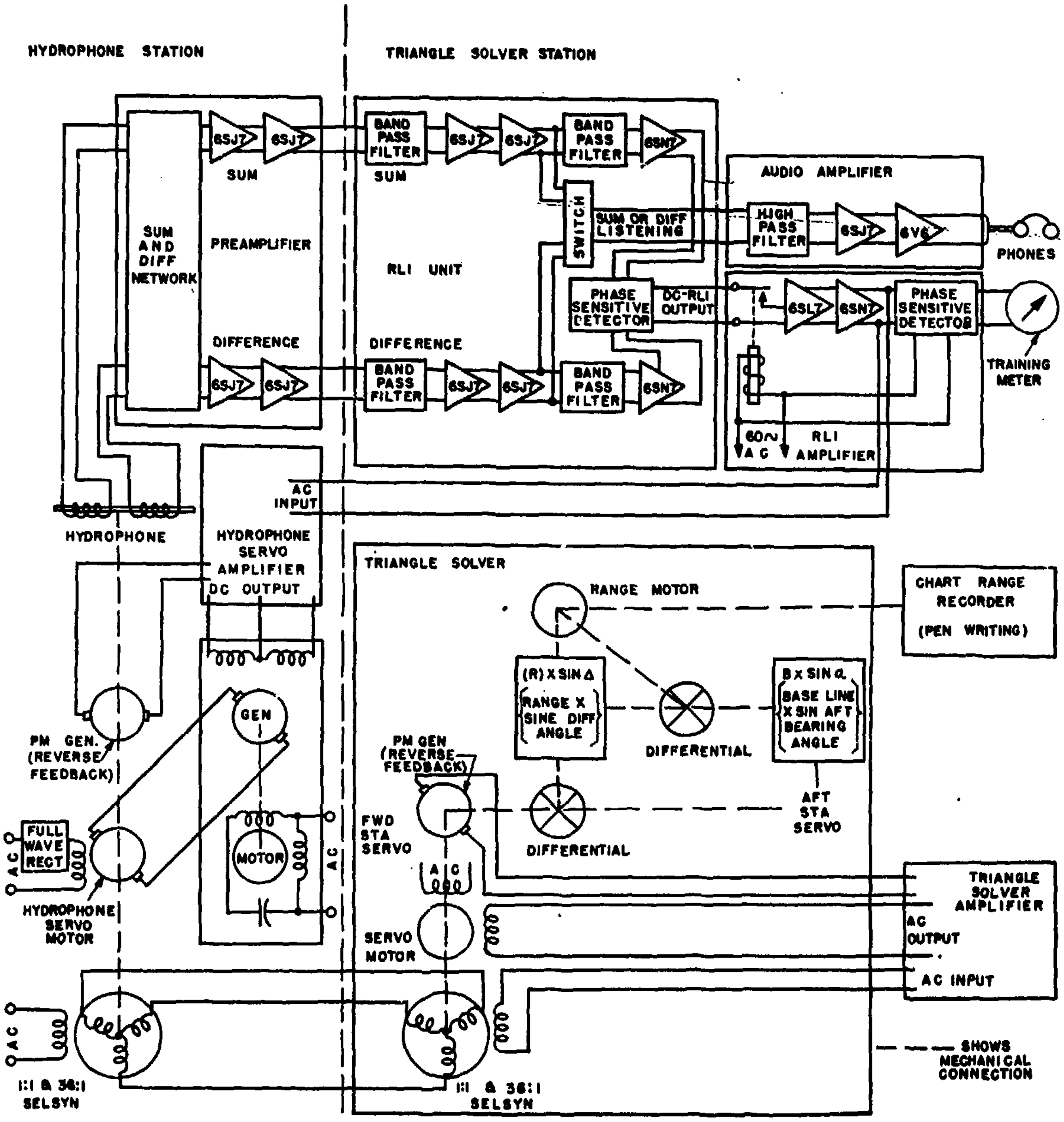


FIGURE 5. Block schematic of *S48* TLR system (forward station).

servo-amplifier as described above, and the triangle solver servo-amplifier is not used.

Triangle Solver and Recorder. The triangle solver is a mechanical device which has been used for computing range at fixed coast-defense gun emplacements and is modified to make it adaptable to this application. The solution of the equation

$$\text{Range} = \frac{\text{sine after angle}}{\text{sine difference angle}} \times \text{baseline}$$

gives the range from the forward hydrophone to the target. This is accomplished mechanically by means of sine and multiplier cams suitably geared together so that when the value of range

is not such as to satisfy the above equation, a contact is closed which varies the value of range until it is satisfied. The values of range so inserted are transmitted by a flexible shaft to a range recorder. A continuous trace of range up to 4,000 yards is recorded on specially ruled paper moving at a rate of approximately ¾ inch per minute.

Hydrophones and RLI System. The remainder of the equipment includes the 3-foot straight split hydrophones, JP-type hydrophone baffles, a preamplifier at each hydrophone station, dual RLI units operating in the 5- to 9-kc band, and an a-c power supply and audio unit at the main control station. The sound system functions identically for either hydrophone station.

After taking the quadrature sum and difference signals in the preamplifier input transformers, each channel is amplified 60 db. This value of fixed gain avoids the complexities of remote control of gain from the main station and is considered a good compromise to minimize overloading on extremely loud signals and yet obtain sufficient amplification of extremely weak signals to override local electric noise pickup. The minimum usable signal is assumed to be 0.25 μv per hydrophone half and this becomes 250 μv at the output of the preamplifiers. The cathode-follower outputs of the preamplifiers are fed to the main control station where they pass through 0- to 20-db step pads before entering the RLI unit.

In the RLI unit, 0.5- to 12-kc band-pass filters are provided to remove low-order 60-c harmonics which would be troublesome in the audio-listening channel and to help prevent blocking by surface ship echo ranging. The filters are followed by a varistor gain control circuit which is controllable over a 38-db range either manually or by AVC. As it was desired that the gains of the two channels always track within 2 db, varistors were chosen for controlling automatically the gain of the sum and difference channels. Following the varistor gain control, the signals are amplified in separate two-stage amplifiers. At this point, either channel of either station may be selected by a switch and amplified to provide audio listening. The signals are also fed to phase-shifting networks which, at the mean frequency, shift the phase of the sum channel 45 degrees and the difference channel 135 degrees to provide a relative phase shift between channels of 90 degrees.

This network resolves the quadrature components (obtained after taking sum and difference) so that the sum and difference signals become in-phase or 180 degrees out-of-phase, depending upon whether the hydrophone is trained to the left or right of the target. The use of a phase-shifting network which accurately shifts the relative phase of the two channels by 90 degrees is desirable for two reasons. Unbalance of the two halves of the hydrophone causes errors in right-left indications if the phase shift varies considerably from 90 degrees; and a phase shift varying considerably with frequency may cause error if the slope of the target noise spectrum is appreciably different from the slope of the noise source used for system lineup. This latter consideration is regarded as important, because the slope of the target noise spectrum may change with range as well as from target to target.

The signals, now 0 or 180 degrees apart, are passed through a 5- to 9-kc filter and a two-stage amplifier and combined in the first phase detector to give d-c output at low level. Because of the difficulty of maintaining balance in a straight d-c amplifier, the d-c output of the phase detector is converted to 60-cycle alternating current in a Brown converter and then amplified. This signal is again rectified in the second phase detector to provide the d-c output necessary to give right-left indications on a d-c zero-center microammeter (full-scale deflection for 1 degree off target). The 60-cycle a-c signal is taken off ahead of the second phase detector to feed the Sperry hydrophone servoamplifier for ATF operation.

Preliminary Tests. The first tests of this system were made with the *S48* lying on the bottom with the hydrophones submerged to a depth of about 20 feet. During this period small hydrophones, located on the conning tower, were used as noise projectors to check the lineup of each hydrophone station. It was found that hydrophone bearings obtained on these noise sources were unreliable, and it was concluded that this was due to hull and conning tower reflections and perhaps also to surface

reflections. This condition was later corrected by locating the projectors within 15 feet of each hydrophone. In order to smooth out the trace on the range recorder, the range rate of the triangle solver was reduced from 150 knots to 60 knots by reducing the speed of the solver motor.

In subsequent operations with live targets, ranges determined by periscope and by echo ranging from the target vessel were compared with ranges obtained on the TLR system. These tests indicated the need for: (1) a range standard which would be accurate within about ± 3 per cent out to 2,000 to 4,000 yards, (2) further smoothing of the triangulation system to give more uniform range traces and, (3) more discrimination against the effects of interfering targets. It was found that, in areas free of interfering targets, ranges up to 3,500 yards on the beam could be obtained under conditions of optimum adjustment of all system components. Figure 6 shows a tracing of one of the best range-time records made during this period and illustrates the rapid fluctuations of indicated ranges.

Revisions to the System. The brass shaft of the forward training gear was replaced by a stainless-steel unit providing twice the torsional stiffness, and the brass roller bearings were replaced by a steel ball race which halved the torque requirements to 12 pound-feet. Four-foot hydrophones, having full lobe reduction and equipped with JP-type baffles, were installed in place of the 3-foot units. The frequency band of the RLI portion of the system was changed from 5 to 9 kc to 9 to 16 kc.

The hydrophone drive response was decreased from 30 degrees per second to 4 degrees per second, the response of the range solver was further reduced to a maximum range rate of 35 knots, the recorder paper speed was increased 20 per cent, and the balancing circuit of the solver servo-amplifiers was improved. A modification to the electronic listening and servo systems was evolved so that, during ATF operation, a scanning action of the hydrophones was obtained. In order to improve the accuracy of reference ranges with which to compare values obtained with the TLR, a more efficient and seaworthy radar reflector and towable buoy assembly was constructed and the target ship was equipped with a type SU radar as the primary range reference beyond 2,500 yards.

Because most of these changes were introduced gradually during intermittent periods of availability of the submarine, the effect of each modification was observed separately. Each change was found to contribute to the accuracy and reliability of the system. In the case of the scanning action of the hydrophones, the greatest benefit was realized when the frequency and amplitude were confined to 4 c and ½ degree, respectively.

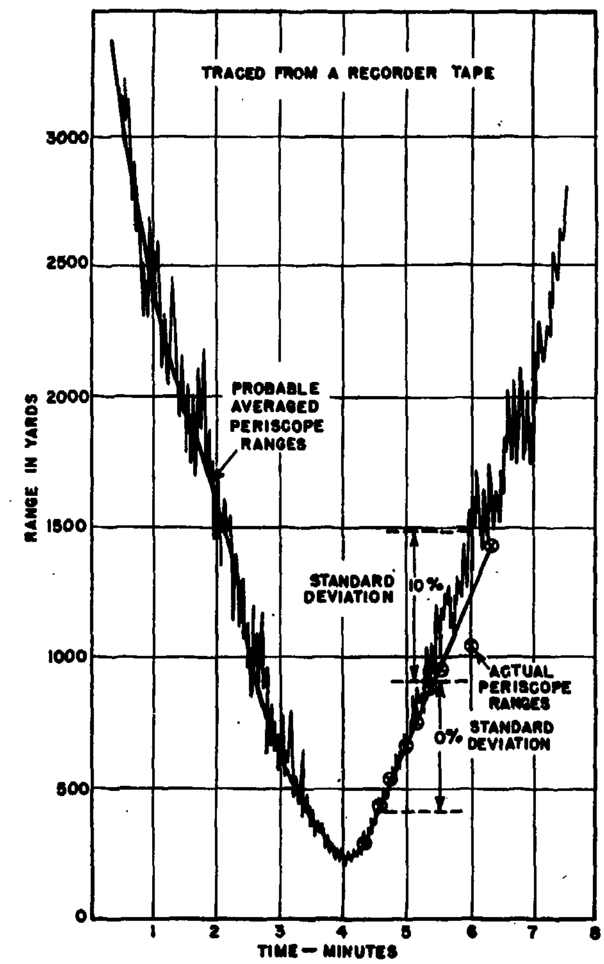


FIGURE 6. Tracing of an early range-time record illustrating the rapid fluctuations of range indication.

Appraisal Tests and Demonstrations. For final tests and appraisal of the system, a 4-week availability period of the USS *S48* was scheduled. In the last 3 weeks of this period, a sec-

ond surface ship was assigned to work with the target vessel ordinarily used so that the performance on single and multiple targets could be evaluated.

With the submarine generally running at 80-foot keel depth and 3 knots, the ranges on a single target, at 3,000 yards and within ± 50 degrees from either beam, were accurate within 15 per cent about three-fourths of the time. Figure 7 shows one of the best range record-

FIGURE 7. One of the best range recordings obtained with the *S48* TLR system.

ings made on a single 15-knot target. Reference data obtained by radar and echo ranging from the target ship are included for comparison. The deviation between TLR and radar or echo ranges does not exceed 10 per cent out to 3,500 yards.

Comments of observers varied from favorable to enthusiastic, with the following points representative of the conclusions. (1) The development of the TLR system should be continued with emphasis on greater reliability, provision of calibration facilities, and better discrimination between multiple targets. (2) The necessary target resolution was not precisely defined, but submarine commanders having war-patrol experience commented informally that the ability to discriminate between equal-strength targets separated 10 degrees or more would probably be satisfactory. (3) A tactical evaluation, preferably under patrol conditions, was considered essential.

Studies of Hydrophones and Interfering Targets

While tests and demonstrations of the *S48* TLR system were in progress, separate development work led to the design of a 5-foot long split hydrophone designated as the NL-124 type, described in Division 6, Volume 11. This unit consists of 10 toroidally wound permanent-magnet magnetostriction elements mounted end-to-end on a stiff brass rod. The sensitivity averages 17 db higher than that of the 3-foot long JP-type hydrophone. When the sensitivities of the five elements comprising each half are selected and averaged, the amplitude balance between halves can be held to within 1 db. Varying degrees of lobe reduction may be incorporated by decreasing successively the sensitivity of the elements toward the ends of the unit.

An extended series of tests was conducted on the surface ship experimental TLR installation to determine the effects on TLR ranges of interfering targets at various intensity levels and angular displacements relative to the desired target. An artificial equalized noise source was located in quiet water about 60 feet deep and about 150 yards from the experimental TLR equipment, so that RLI patterns of 3-, 4-, and 5-foot split hydrophones having full, intermediate, and no lobe reduction were determined.

The initial tests were made using the 5- to 9-kc frequency band. A graphical method was developed whereby one RLI pattern could be superimposed on another but displaced by varying amounts to simulate angular and amplitude differences comparable to those which might be expected from ships in a convoy. The results obtained by this method checked quite closely with measured interference effects using two

artificial signals. It was found that appreciable bearing errors were introduced, particularly for high interfering levels, when the targets were separated by angles less than the angle between the on-target and secondary zeros of the RLI pattern. These values, as measured

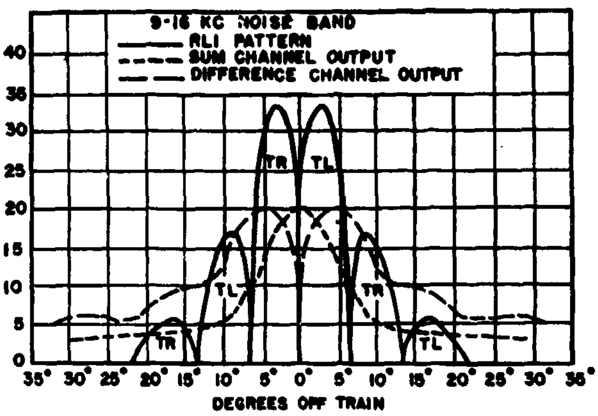


FIGURE 8. Sum, difference, and RLI patterns of NL-124 hydrophone without lobe reduction for 9- to 16-kc band.

using 5-foot hydrophones and the 5- to 9-kc band, were about 17 degrees for full lobe reduction and 13 degrees for no lobe reduction.

The NL-124 hydrophone without lobe reduction was also tested with an RLI modified to operate in the 9- to 16-kc band. Figure 8 shows the sum and difference directivity characteristics of this hydrophone unit and the resulting RLI characteristic. In this case, the separation between the on-target and secondary zeros of the RLI response is only 6.5 degrees. Figure 9 shows the probable error introduced by interfering targets of various signal strengths and angular positions with respect to the main target. When using this unit, strong interference less than 6 degrees from the target can still introduce an appreciable bearing error. Greater separations do not appear to be serious.

Fleet Submarine Installation

As a consequence of the encouraging results obtained in the tests of the *S48* TLR system, the Bureau of Ships requested that this equipment be modified to permit its installation on a new-construction submarine for evaluation of its performance under patrol conditions. Because of the limited time available for adjusting and testing the system after installation, it was decided that no basic design changes other than in the training assembly should be made. Every effort was made, however, to improve the performance of those elements of the system which previous tests had shown to be deficient and to anticipate the operational and maintenance problems which might arise during war patrol.

Since the unit was still considered to be primarily an experimental model, it was believed necessary to have all the operational parts readily accessible. For this reason the main control station is located in the maneuvering room where access to three sides of the main stacks is possible.

The forward hydrophone station is located between frames 22 and 23 and the after station between frames 123 and 124. This arrangement results in a base line of 233.5 feet, an increase of 14 per cent over that of the *S48* installation. The training assemblies are equipped with extra-heavy stainless-steel shafting in order to attain a high degree of torsional rigidity. The

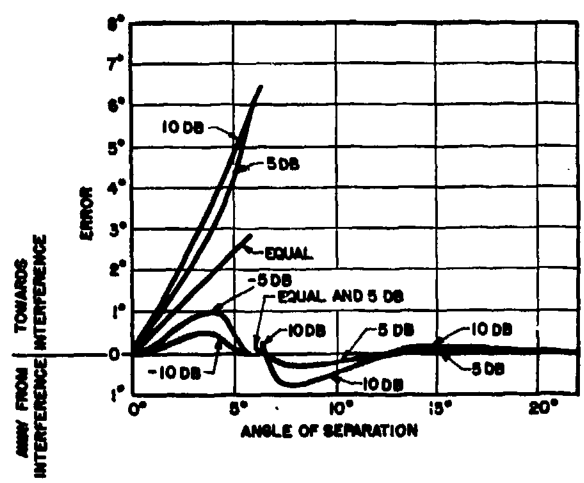


FIGURE 9. Probable angular errors due to interfering targets when using NL-124 hydrophone without lobe reduction in the 9- to 16-kc band.

drive motor, repeater synchro, and spur gear assembly is bolted to a support which is machined so that the drive pinion is automatically aligned and meshed tightly with the main driven gear on the shaft, thereby eliminating backlash at this critical point. The motor and gearbox frame is bolted rather than welded to a flange which terminates the casing of the

training assembly in order to eliminate welding strains during installation and simplify field installations.[4]

The main operating station in the maneuvering room is functionally centralized, containing all components requiring adjustment during operation. Transmission of range and bearing information to the conning tower is by means of a range recorder and a synchro system which repeats bearings from the forward and after stations. The conning tower components are located so that TLR data are available for the conning officer, plotting officer, and the *torpedo data computer* [TDC] operator during attack or evasive maneuvers. An intercommunicating system provides for exchange of operational data between the conning tower and the TLR operator.

RLI and Listening Equipment. The RLI and listening equipment provided for this installation is basically the same as that finally incorporated in the *S48* system and indicated in the block diagram, Figure 5, but a number of modifications are incorporated to improve the performance and adapt the equipment to the requirements of a new-construction boat.

The hydrophones supplied are of the 5-foot NL-124 type with no lobe reduction. These units, having maximum sensitivity in the 9- to 16-kc band, are equipped with NL-129A type baffles, described in connection with submarine listening equipment, which provide a front-to-back differential of 20 db to 23 db in that region. The aft hydrophone and baffle assembly is shown in Figure 10.

New preamplifiers were constructed, having reduced electric noise pickup and transformer-coupled output.

Equalizers are used which provide a positive slope of about 6 db per octave to the overall frequency characteristic (hydrophone and amplifiers) up to 16 kc, to compensate for the negative slope of the average screw noise spectrum. This leads to the summation of a wider band of frequencies, and the resulting sum, difference, and RLI response patterns should be narrower than those shown in Figure 8, with consequent reduction of interference from secondary targets. The listening channel is provided with high-pass filters having cutoffs at 500, 1,500, and 4,500 c, which appear to be optimum for use with 5-foot hydrophones.

A new power-supply unit furnishes regulated power for the entire sound amplifier system and incorporates a signal generator which supplies noise of proper frequency distribution to the test projectors, located topside near the hydrophones. The 150- and 275-volt outputs are constant to within 0.5 volt for a-c line variations from 90 to 130 volts, as a precaution

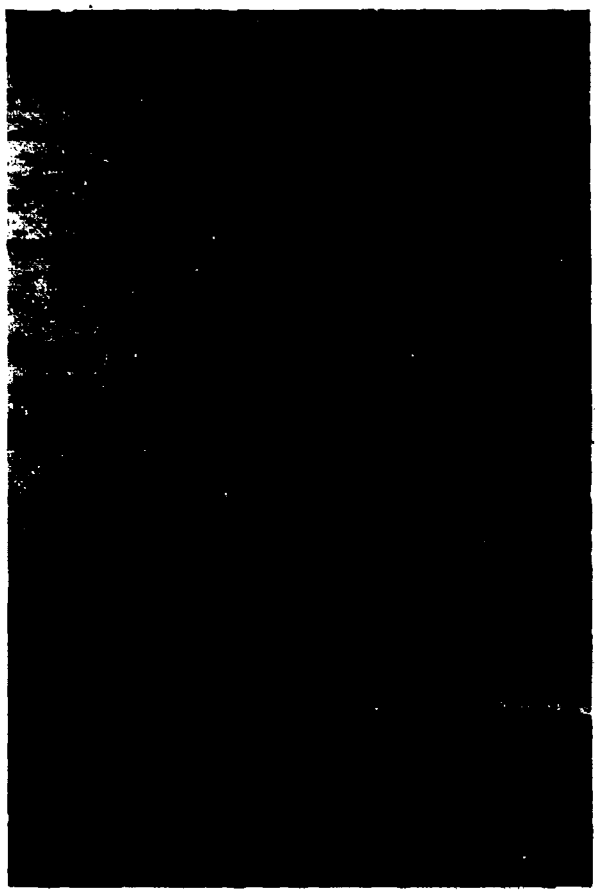


FIGURE 10. Aft TLR hydrophone installation on a fleet-type submarine.

against the introduction of transients in the RLI output. The sonar talkback system which provides communications between the main control station and the conning tower is a component of the Model JT sonar equipment.

The main station sound equipment (for both hydrophones) is housed in a cabinet 43 inches high, $20\frac{5}{16}$ inches wide, and $11\frac{1}{32}$ inches deep, with the various chassis readily accessible by

hinged or removable cover plates. A front view of this unit is shown in Figure 11.

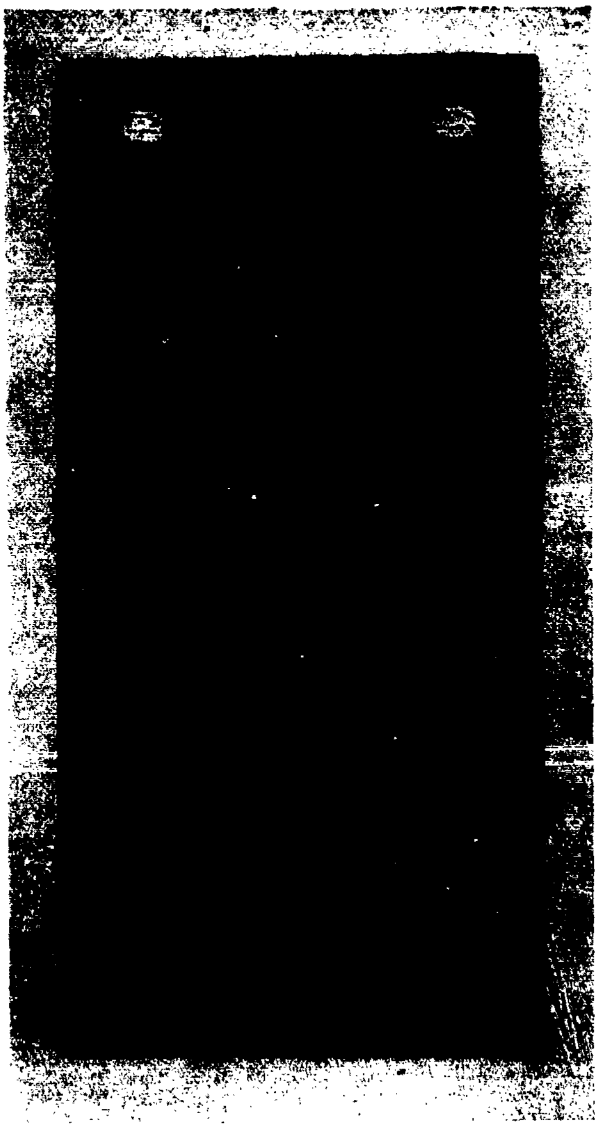


FIGURE 11. Main station sound equipment used on fleet-type submarine.

Servo-amplifier, Range Solver, and Recorder. In the servo-amplifier, range solver, and recorder equipment only a few relatively minor changes were made in adapting the components used in the *S48* installation for use on the new-construction submarine. Lineup of the bearing-repeat dials to correspond to hydrophone bearings was difficult in the *S48* installation and this was remedied by increasing the dead spot near zero on the coarse synchros and bringing out mechanical adjustments ($\pm$ 1.0 degree) from the fine synchros to the exterior of the triangle-solver cabinet.

One range recorder is installed with the main control equipment and a second recorder is installed in the conning tower. The main station control equipment is shown in Figure 12, and the range recorder in Figure 13.

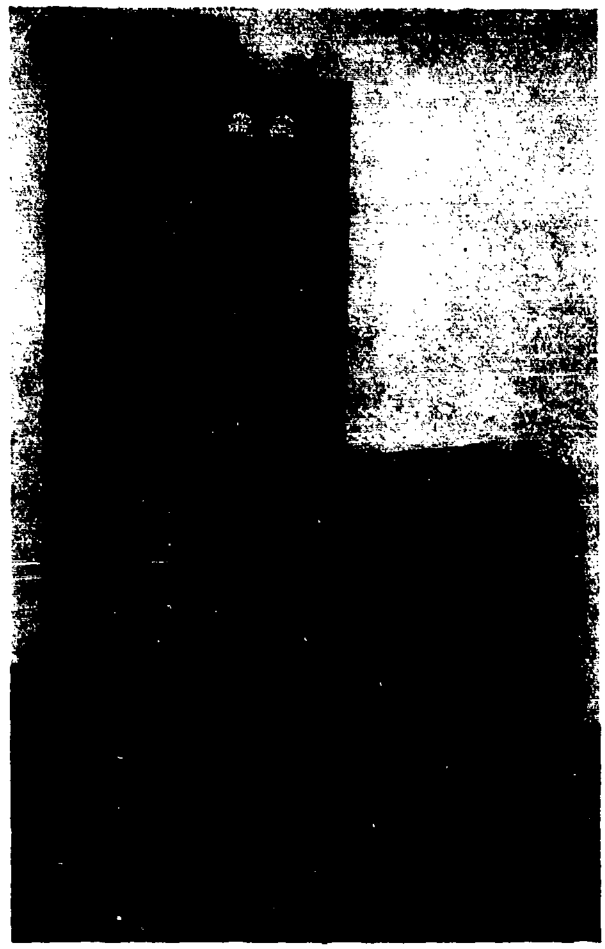


FIGURE 12. Main station control equipment used on fleet-type submarine.

Tests. Only preliminary adjustment and testing of this TLR installation were possible prior to the time responsibility for the development was transferred to the Naval Research Laboratory. Dockside measurements were made to determine the bearing accuracy capabilities of the system including the hydrophone drives and bearing-repeat synchros. The maximum bearing error of the system was thus determined to be 5.2 minutes, with a mean error of

5.0 minutes. Tests of the electronic components indicated adequate performance in all respects.

During a trip of the submarine to deep water, an opportunity was afforded to coordinate periscope and TLR ranges over a period of several hours. One run made at this time checked within 6 per cent out to 4,500 yards. Owing to the limited data obtained and because no systematic lineup of the TLR installation had previously been possible, it is not believed that this run is necessarily typical of average performance of the system. At the time responsibility for the system was transferred to the Naval Research Laboratory, a 14-day test period had been scheduled primarily for further operational evaluation of the TLR system.

12.5 PREPRODUCTION UNITS

Concurrently with the work of transferring the experimental TLR system from the *S48* to a new-construction submarine, arrangements were made with the Submarine Signal Company for the procurement of five preproduction units for additional war patrol appraisal tests on other new-construction boats. These units are designated by the Navy as Model XJAA listening-ranging equipment.

FIGURE 13. Range recorder used on fleet-type submarine (cover removed).

Drawings and specifications of the *S48* system and complete information on subsequent improvements to this equipment were furnished to the contractor. Further assistance was also made available in the form of consulting services from engineers familiar with the original development work.

None of the preproduction units was completed prior to transfer of the project to NRL. The manufacturer's plans at that time, however, indicated that the XJAA units would incorporate hydrophones, baffles, and calibration projectors identical with those used in the last laboratory installation. The designs prepared for RLI units also retain the basic features of

the laboratory models, but the control station equipment layouts are designed to permit these components to be installed in the conning tower.

12.6 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The experience obtained with the experimental units of this equipment led to the conclusion that a number of improvements could be made by further development work.

At 6 knots, the torque due to water drag on the hydrophone varies between 0 and 42 pound-feet, depending on the bearing, and at 3 knots the maximum torque is 10.5 pound-feet. It is of major importance that the system be capable of operating free from the bias that can be caused by this torque and also, to some extent, by frictional forces. Tests indicate that the best means of minimizing these effects is to operate with overall system sensitivity below hunt yet sufficiently responsive so that a scanning action is obtained. A scanning frequency of about 4 c with an amplitude of ± 0.5 degree appears to approach a good averaging of the correct bearing. Further developmental work should include a thorough investigation to determine the optimum dynamic response for reducing bias to the absolute minimum.

Further evaluation of the experimental equipment on new-construction submarines may indicate the need for additional reduction of the effects of interfering targets. This is an inherent limitation to this type of system which may be minimized, but cannot be entirely eliminated. It is believed that a clarification of the tactical requirements is needed in determining the need for further work on this problem. Action of the system in the presence of interfering targets is dependent on a number of factors: (1) the relative signal levels of the prime and interfering targets, (2) the angular separations of the targets, (3) the bearings of the targets relative to the submarine, (4) the design of the hydrophone and baffle assemblies, and (5) the frequency band in which the bearing deviation system operates. One method of minimizing the interference problem is by decreasing the width of the main and side lobes of the hydrophone which may be accomplished by operating at a higher frequency band than 9 to 16 kc or by using a longer hydrophone. A system designed to operate at higher frequencies should be based upon determinations of the available target energy, the variations in the slope of the energy spectrum with range and type of source, and also on the feasibility of developing hydrophones of suitable sensitivity in the desired band.

An ultimate limitation to the accuracy of a submarine triangulation system is the precision with which the hydrophones can be zeroed with reference to the base line. Alignment by means of a reference noise source mounted near each hydrophone is possible to within ± 0.05 degree in the experimental system which means that an alignment error as great as ± 0.1 degree may be present. For a base line of 233 feet, an error of this magnitude causes a range error of approximately 185 yards for a target at 090 degrees relative bearing and 3,000 yards range, indicating the importance of increasing alignment precision. In this connection, the advantages offered by installed ringed hydrophones should be investigated.

In the experimental equipment, instabilities have been present which cause shifts in the zero alignment of the system. It is recommended that tests be conducted to determine whether this condition is due to system variations or is inherent in the medium.

In addition to the possible system improvements noted above, it is believed that coordination of the use of the triangulation system with submarine attack and evasive tactics may result in auxiliary uses, such as tracking separate vessels with each of the two hydrophone stations.

Chapter 13

TORPEDO DETECTION STUDIES AND SYSTEMS—MVP AND TDM

Torpedo noise generally occurs at an intensity level high enough to be detected above ship's self-noise and at a range great enough to warn the listening ship to maneuver in time to prevent the torpedo's hitting its mark. The projects for *merchant vessel protection* [MVP] and WCA-2 *torpedo detection modification* [TDM] provided information regarding torpedo noise and resulted in recommendations and equipment for torpedo detection.

The MVP project consisted mainly of tests to ascertain what conditions existed. Much of the value of these tests and measurements lies in the fact that they included several types of gear and were not confined to special requirements of sonic equipment. Analyses of noise from many types of torpedoes showed that the frequency distribution ranged from sonic to supersonic with maximum intensity of all types tested in the sonic range from 300 to 800 c. Measurements of ship's self-noise, compared with the torpedo noise measurements, showed that the optimum operating region is below 3 kc for a nondirectional pickup unit, but that detection is possible at higher frequencies for directional units.

The conclusion that torpedo frequency components exist in the supersonic as well as the sonic region led to work on the TDM. With this knowledge, experimenters realized that the supersonic WCA-2 equipment, already installed on submarines, could be modified to detect torpedoes. This enabled quick installation of the new equipment without the addition of much gear to already crowded submarines. Another conclusion from the MVP tests recommended many features of the directional JP through-the-hull gear, patterned after a British continuously rotating system studied.

Sonic Protection for Merchant Vessels Against Torpedo Attacks [MVP]

13.1 INTRODUCTION

It was believed that if fast merchant ships could detect torpedoes at ranges of 1,000 yards or more and submarines at ranges up to 1,000 yards, they could take action soon enough to reduce the possibility of being hit. This would preclude the necessity of being held down to convoy speeds of 10 to 12 knots.

Two types of torpedo detection devices were already in use. The first of these,[1] a commercial (Electro-Protective Corporation) fixed hydrophone [E-P] system installed on a number of U. S. merchant ships, employed a hydrophone on each side of the hull and gave an audible warning signal together with a visual indication of port or starboard approach. The second, a British device designed for warships, used a continuously rotated hydrophone in a streamline dome. This system provided both an audible indication and accurate bearing information but required constant monitoring. Although a scanning equipment designed for screening anchored vessels against submarines (*Anchored Vessel Screening*, described in Division 6, Volume 15) was sufficiently developed to be considered for possible use on moving ships, this application of the equipment had not been investigated. Some information was available in British reports on the effectiveness of the rotating type of torpedo detection device, but no reliable performance data existed for the E-P fixed hydrophone equipment. Further, no adequate information existed on two factors of fundamental importance to the torpedo detection problem: the self-noise (at or near the hull) of merchant ships and the noise from torpedoes. The program undertaken, therefore, consisted of (1) measuring the sound output of torpedoes, (2) measuring ship self-noise at various speeds, and (3) testing and evaluating each of the three types of equipment to determine its capabilities for detecting submarines from fast-moving merchant ships.

Conclusions

A number of broad conclusions were reached during this program.

1. First it was concluded that anchored vessel screening equipment in its state of development at the time of testing was not adequate

for detecting submarines at ranges up to 1,000 yards from fast-moving merchant vessels.

2. Sonic detection of submarine torpedoes at ranges up to about 2,000 yards from fast-moving merchant ships is feasible under moderate sea conditions with both the rotating and fixed hydrophone types of systems, but care must be exercised if ranges of this order are to be consistently obtained.

3. Improvements to the fixed hydrophone system then available were necessary to increase its reliability for routine use on merchant ships. These improvements included raising the recommended sensitivity settings, changing the circuit to improve selectivity between torpedo and ship noise, and broadening the response characteristics of the hydrophones.

4. Compared with the fixed system, the rotating type had the advantages of more accurate bearing determination and greater possible range but the disadvantages of greater complexity, increased difficulty of installation, and the necessity for constant monitoring.

13.2 TORPEDO NOISE MEASUREMENTS

A laboratory ship, used for the torpedo noise tests, was stationed approximately 2,000 yards from the torpedo firing point. The noise from

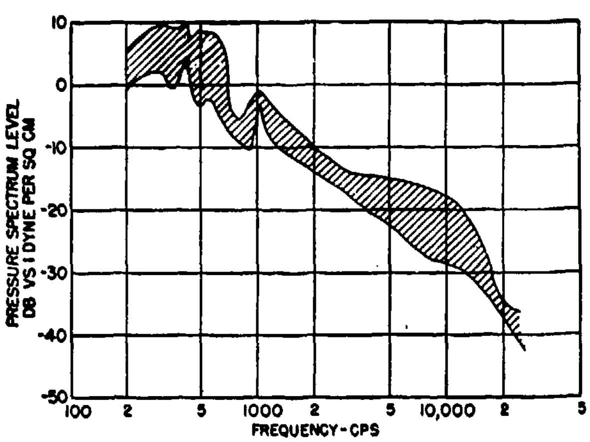


FIGURE 1. Limits of noise from U.S. Mark XIV torpedoes.

each torpedo was picked up by a 3A-type hydrophone (Bell Telephone Laboratories) and recorded from the instant of firing until the torpedo had passed 1,000 to 2,000 yards beyond the hydrophone. Analyses of the torpedo noise were made by playing back each recording through various filters, and plotting curves

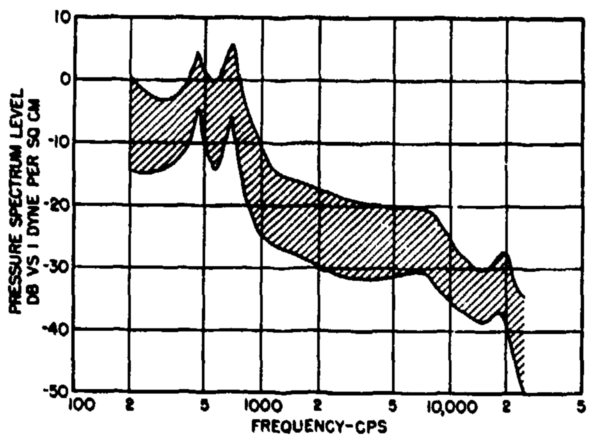


FIGURE 2. Limits of noise from U.S. Mark XVIII torpedoes.

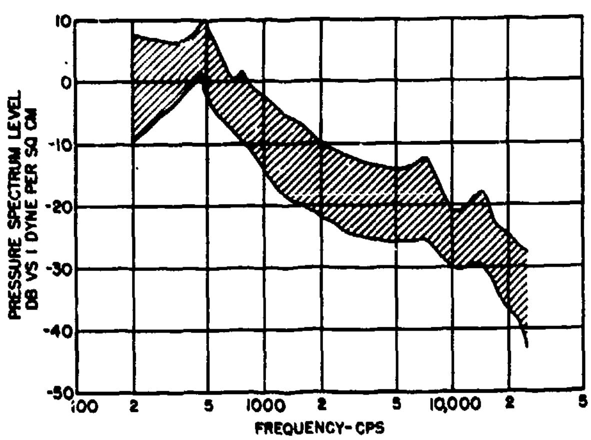


FIGURE 3. Limits of noise from British Mark VIII torpedoes.

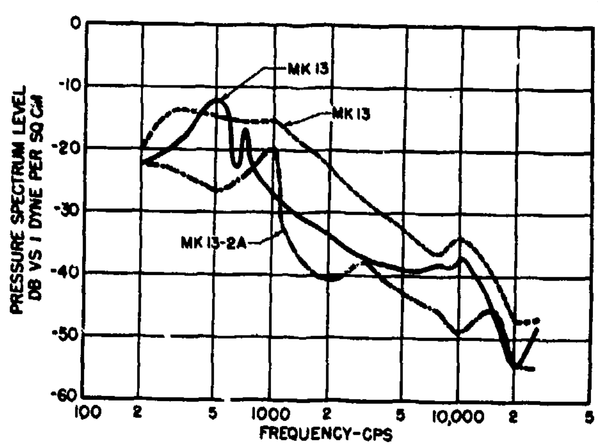


FIGURE 4. Noise from U.S. Mark XIII and Mark XIII-2A torpedoes.

showing the pressure spectrum level within the range 200 c to 25,000 c for torpedo distances of 1,000 yards and 1,500 yards on the approach runs.

Examination of the noise spectra curves segregated according to torpedo type (Figures 1 to 4), indicates that although the character of the noise from all types is roughly similar, quite wide variations exist in the intensity of the noise not only with different types of torpedoes but also between individual runs of the same type of torpedo. The maximum intensity for all types occurs in the region between 300 c and 800 c. Figure 5 shows the pressure spectrum level at 1,000 yards for all types tested. These tests are discussed in detail in available reports.[2,3]

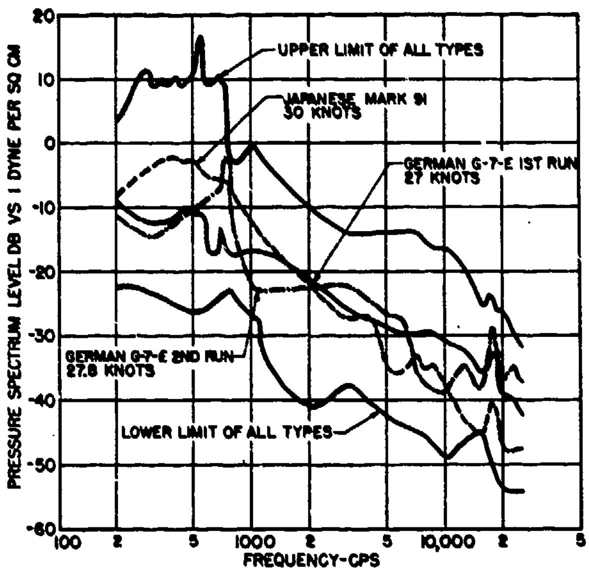


FIGURE 5. Limits of torpedo noise at 1,000 yards for all types measured.

13.3 SHIP SELF-NOISE MEASUREMENTS

Merchant Ship Noise

Measurements of merchant ship self-noise were made on a modern tanker of approximately 19,000 tons displacement having a single screw driven by a steam turbine through double reduction gears and capable of speeds up to about 18 knots. A photograph of this vessel is shown in Figure 12. Twelve pickup

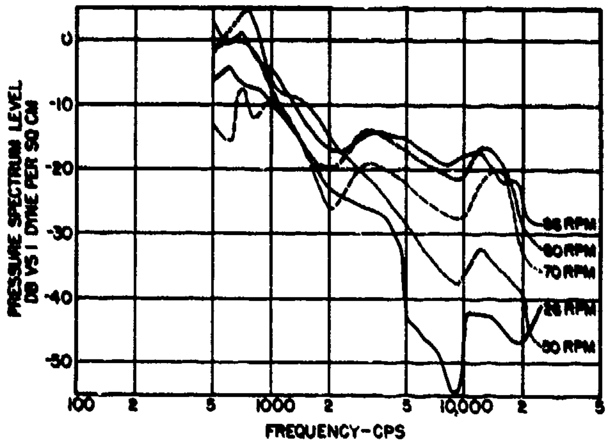


FIGURE 6. Variation of self-noise of SS *Colorado* with propeller speed.

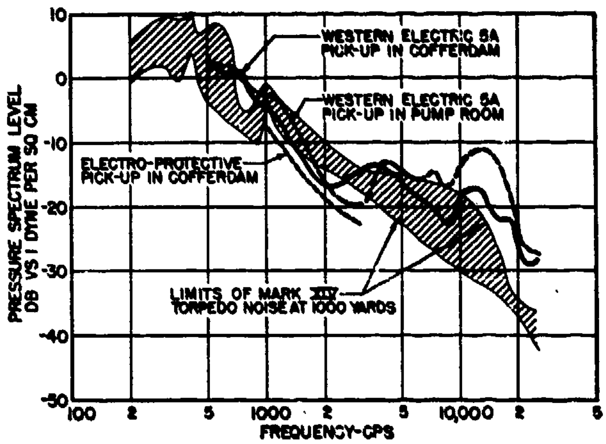


FIGURE 7. Variation of self-noise of SS *Colorado* at 17 knots with type and location of pickup units, compared with U.S. Mark XIV torpedo noise.

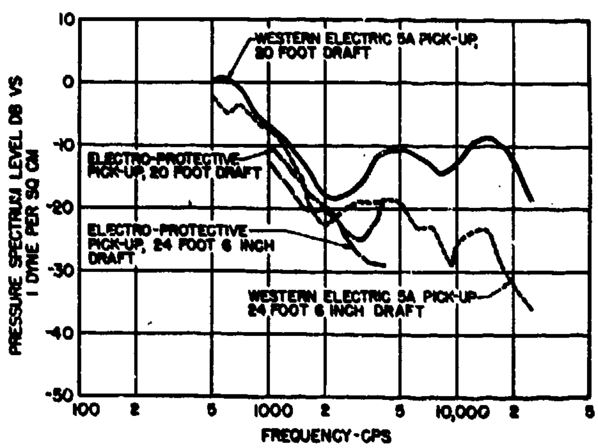


FIGURE 8. Comparison of average self-noise of SS *Colorado* at 70 rpm for 20-foot, 0-inch and 24-foot, 6-inch drafts.

units were installed at locations inside and just outside the hull of this ship. These units were of four different types. Types AX58 and JO hydrophones (Brush Development Company) were externally mounted; Type 5A (Bell Telephone Laboratories), and modified VP-5 (Brush) vibration pickups were mounted inside the hull. The inside-mounted units measured vibration of the ship's plates. Sensitivity and pattern calibrations of these units may be found in Division 6, Volume 11.

Self-noise measurements were made in various frequency bands by means of the 12 pickup units while the ship was running on an even keel at a 24.5-foot draft at each of four speeds: 26, 50, 70, and 86 rpm, corresponding approximately to water speeds of 5, 10, 14, and 17 knots. In addition, measurements were made with the ship ballasted at an even keel draft of 20 feet and running at 70 rpm.

Using these noise data, curves were plotted showing the frequency distribution of the self-noise in the range from 500 to 25,000 c. Combinations of these curves indicate the self-noise variation with speed of the ship (Figure 6), with type and location of pickup unit (Figure 7), and with change of draft (Figure 8). The self-noise values are given in terms of pressure spectrum levels referred to 1 dyne per sq cm for sound in the water (by reference to the acoustic calibrations mentioned above) and thus are directly comparable to the measurements of torpedo noise.

The measurements indicate that the effect of increase in speed of the ship is confined mainly to an increase in the higher (above 2 kc) frequency components of the self-noise. Comparison of the self-noise spectra with the torpedo noise spectra indicates that, with a nondirectional device, the optimum listening range of frequencies for torpedo sounds is in the region below 3 kc. The self-noise is greater, particularly at the higher frequencies, for a shallower draft of the ship. No significant difference was detected with change in the longitudinal position of the pickup unit from midships forward to the cofferdam section. The technique and results of the self-noise measurements on the merchant ship are discussed in detail in reference 2.

Destroyer Noise in Streamline Domes

Measurements were made of the noise in the 50-inch QBF and 100-inch JK domes on the USS *Semmes*, a four-stack destroyer assigned to experimental work. This vessel has twin screws driven through reduction gears by high- and low-pressure steam turbines. Two series of measurements were made, the first utilizing the QBF and JK transducers as hydrophones, and the second utilizing a Type 3A hydrophone (Bell Telephone Laboratories) mounted successively in each of the two domes. In each case the speed of the ship was varied in approximately 5-knot steps from 0 to 25 knots.

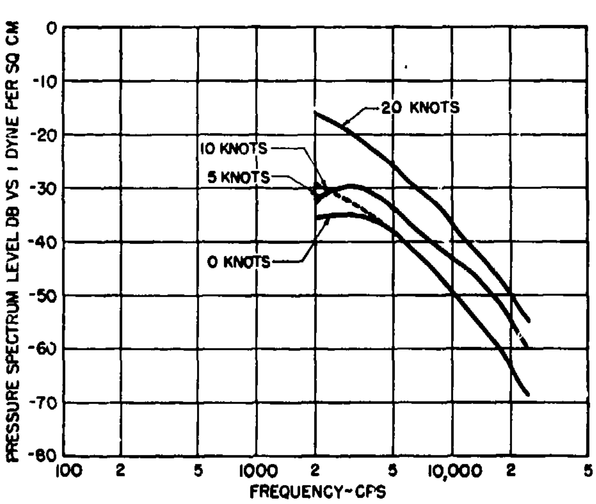


FIGURE 9. Self-noise as measured by the JK transducer in dome on the USS *Semmes*.

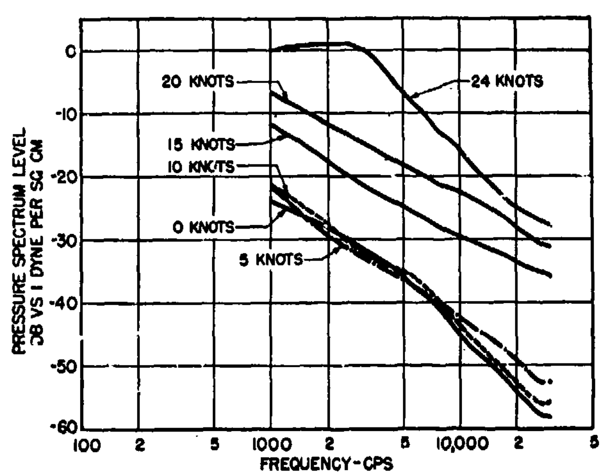


FIGURE 10. Self-noise vs speed as measured by BTL 3A hydrophone in QBF dome of USS *Semmes*.

Curves (Figures 9 and 10) indicate the frequency distribution of the noise in the range from 1 to 30 kc. The measurements, made using the QBF and JK transducers, have not been compensated to eliminate the effects of directionality of these units at the higher frequencies. Thus, they are not directly comparable with those made using the 3A hydrophone which is virtually nondirectional in the frequency region investigated, but the measured differences are approximately as expected. The pressure spectrum levels fall roughly 6 db per octave for the nondirectional 3A pickup and 12 db per octave for the JK hydrophone.

In general, these measurements[4,5] indicate that the noise in the QBF dome is very nearly constant with speed throughout the 1- to 30-kc frequency range, up to approximately 10 knots, and rises at the rate of about 2 db per knot above that speed. In the JK dome the noise increases appreciably before a speed of 10 knots is reached, but rises only about 1½ db per knot above that speed.

Modified Through-the-Hull Equipment

The modified through-the-hull equipment was designed to provide a system capable of detecting the noise of approaching torpedoes and of determining accurately their relative bearing from the target vessel. It includes an 18-inch magnetostriction line hydrophone, a power training mechanism, and a cathode-ray tube indicator. The hydrophone shaft rotates continuously at 60 rpm. The CRO uses a circular sweep synchronized with the hydrophone rotation. A target is indicated by brightening and increased radial displacement of the trace. The acoustic response of the system was limited to the 20-kc to 30-kc band where the 18-inch hydrophone is fairly directional. Tests from a small ship laying to showed that torpedoes, detected on firing, can be followed approximately 2,000 yards beyond the hydrophone. This equipment, developed by CUDWR-NLL, is based on the JP through-the-hull equipment and a British continuously rotated hydrophone in a streamline dome.

FIGURE 11. Modified through-the-hull interior equipment.

13.4 DETECTION EQUIPMENT

The performance of a continuously rotated torpedo detection system modified from through-the-hull listening gear, described in Chapter 7, was investigated on a small laboratory vessel. The equipment was modified by replacing the hand training mechanism with an electric motor and gear reduction unit isolated from the hull and hydrophone shaft by flexible mounts and couplings. The resulting rotational speed of the hydrophone shaft was 60 rpm and the entire assembly was free of any significant mechanical noise. This mechanism is shown in Figure 11.

The 3-foot straight magnetostriction hydrophone, normally used with the through-the-hull gear, was replaced by an 18-inch unit of the same type capable of being installed in a standard 19-inch dome. The electric connections from the hydrophone were made by means of gold-plated slip rings on the rotating shaft and gold-plated copper braid brushes which gave quiet operation both electrically and mechanically. The response of the system was limited by filters to a frequency band 10 kc wide which could be translated continuously, by means of a heterodyning system, through the range from 5 kc to 100 kc. In addition,

some tests were made using a wide-band sonic amplifier with high-pass filters having cutoffs at 600 c and 2 kc.

The effects of acoustic signals reaching the hydrophone were exhibited on a long-persistence type screen of a cathode-ray tube using a circular sweep synchronized with the rotation of the hydrophone shaft. In the absence of targets, the trace on the cathode-ray oscilloscope [CRO] was essentially circular except for own-ship's propeller noise indications close to 180 degrees while the listening ship was underway. A torpedo or ship signal was indicated by a brightening and a greater radial displacement of the trace on the relative bearing of the target.

TESTS AND OBSERVATIONS

Only one trial was made of the response of the rotating detection equipment to actual torpedo signals. As no dome was installed over the hydrophone during these tests, it was not possible to make observations with the listening ship underway. Several firings of 30-knot U. S. Mark XIII (aircraft type) torpedoes were observed. With the laboratory ship laying to (with engines and generators running) near the torpedo course at a distance of about 1,000 yards from the firing barge, it was qualitatively observed that the frequency band from 22 to 32 kc gave about optimum balance between deflection amplitude and sharpness of bearing for this type of torpedo. In this frequency range, the torpedoes were detected immediately on firing and could be followed until they had traveled slightly more than 2,000 yards beyond the listening ship. Calibration of the system indicated that ½-inch CRO deflections, obtained for torpedoes at 1,000 yards, corresponded to a pressure spectrum level of approximately −62 to −59 db vs 1 dyne per sq cm, which checks the levels measured for this type of torpedo. Further observations made under the same listening ship conditions indicated that, although greater ranges could be obtained at lower frequencies, bearing indications became increasingly broader with decreasing frequency, but it is very doubtful that any range advantage would have been found at the lower frequencies with the listening ship underway.

The development time available was insufficient to permit a more thorough investigation of the optimum frequency range or to determine directly the effects of underway noise of the listening ship with a dome over the hydrophone and of different rotational speeds of the hydrophone upon torpedo detection ranges.

The equipment modifications and the technique and results of the tests are described more fully in reference 6.

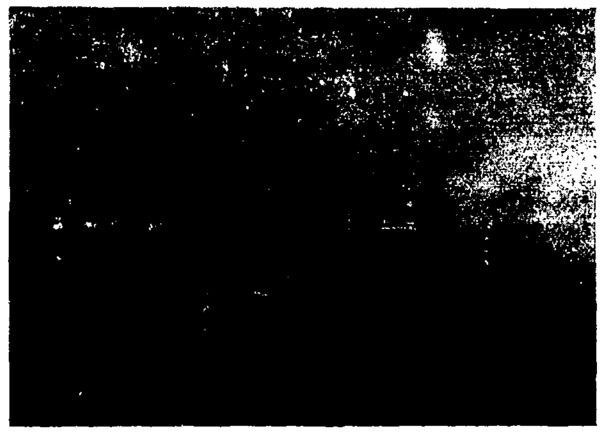


FIGURE 12. The SS *Colorado* used for tests of E-P equipment and for merchant ship self-noise measurements.

Electro-Protective [E-P] Torpedo Detector

The Electro-Protective [E-P] Corporation torpedo detector is a device used on merchant vessels to detect the noise of torpedoes and to indicate whether the torpedoes are approaching from port or starboard. The equipment consists of two nondirectional hydrophones and an electronic indicator mechanism. The hydrophones, installed inside the hull on each side of the ship, are modified vibration pickups, sensitive to sounds from 1,500 c to 3,000 c. The indicator mechanism is actuated by signals from either of the two hydrophones. When the sound from one of the pickups is sufficiently intense, an indicator light and a loudspeaker provide a visible and an audible alarm. In tests of this device conducted by CUDWR-NLL, detection ranges of up to 2,000 yards were obtained in moderate seas.

The E-P torpedo detector is designed to provide a means of warning a merchant ship when a torpedo is in the vicinity and to indicate from which side, port or starboard, it may be approaching. This is accomplished by using two hydrophone units, one on each side of the ship, and feeding their outputs into an electric circuit which utilizes an increase in the output of one of the units to operate a port or starboard indicator light and an audible alarm. The hydrophone units consist of modified Type VP-5 crystal vibration units (Brush Development Company), and are mounted inside the hull near the bow and well below the waterline. The two units are transformer-coupled to the amplifier indicator rack shown in Figure 13 and located in the wheel house.

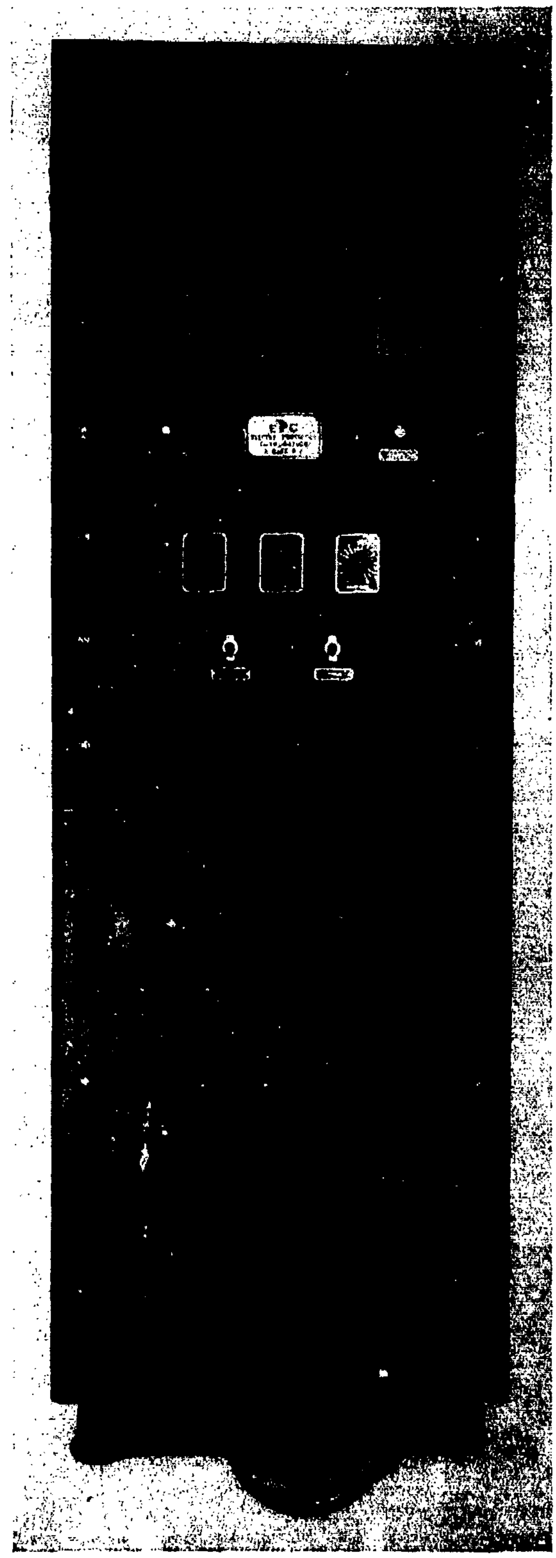


FIGURE 13. Amplifier-indicator rack of the Electro-Protective torpedo detection equipment.

CIRCUIT ANALYSIS

As indicated in the schematic diagram, Figure 14, two channels are provided, one supplied by the port and the other by the starboard hydrophone. Each comprises a three-stage audio-amplifier circuit (V-101, V-102, V-103 for the port hydrophone; V-109, V-110, V-111 for the starboard), and an alarm circuit consisting of a channel section (V-104, V-105, V-112, and V-113), and a common section. A relay in each channel (K-101 and K-102), referred to as the channel relay, is actuated by the plate current in the corresponding relay control tube, V-105 (port), which has a milliammeter, M-101, inserted in the cathode circuit to indicate this plate current. The channel relay is caused to close whenever the signal level becomes high enough to give a plate current of approximately 4.5 milliamperes. Closing of this relay partially completes the circuit including the channel alarm lamps (port, red; starboard, green) and starts the process which actuates the alarm relay (K-103). The alarm relay is controlled by the relay control tube, V-114. With the closing of the channel relay the grids of V-114 are connected to the cathode-bias circuit through R-146, which taken with the grid condenser, C-139, forms a time delay network. A delay of from 0 to 5 seconds, depending on the setting of R-146, is thus provided, after which the plate current reaches a sufficient value to actuate the relay. Closing

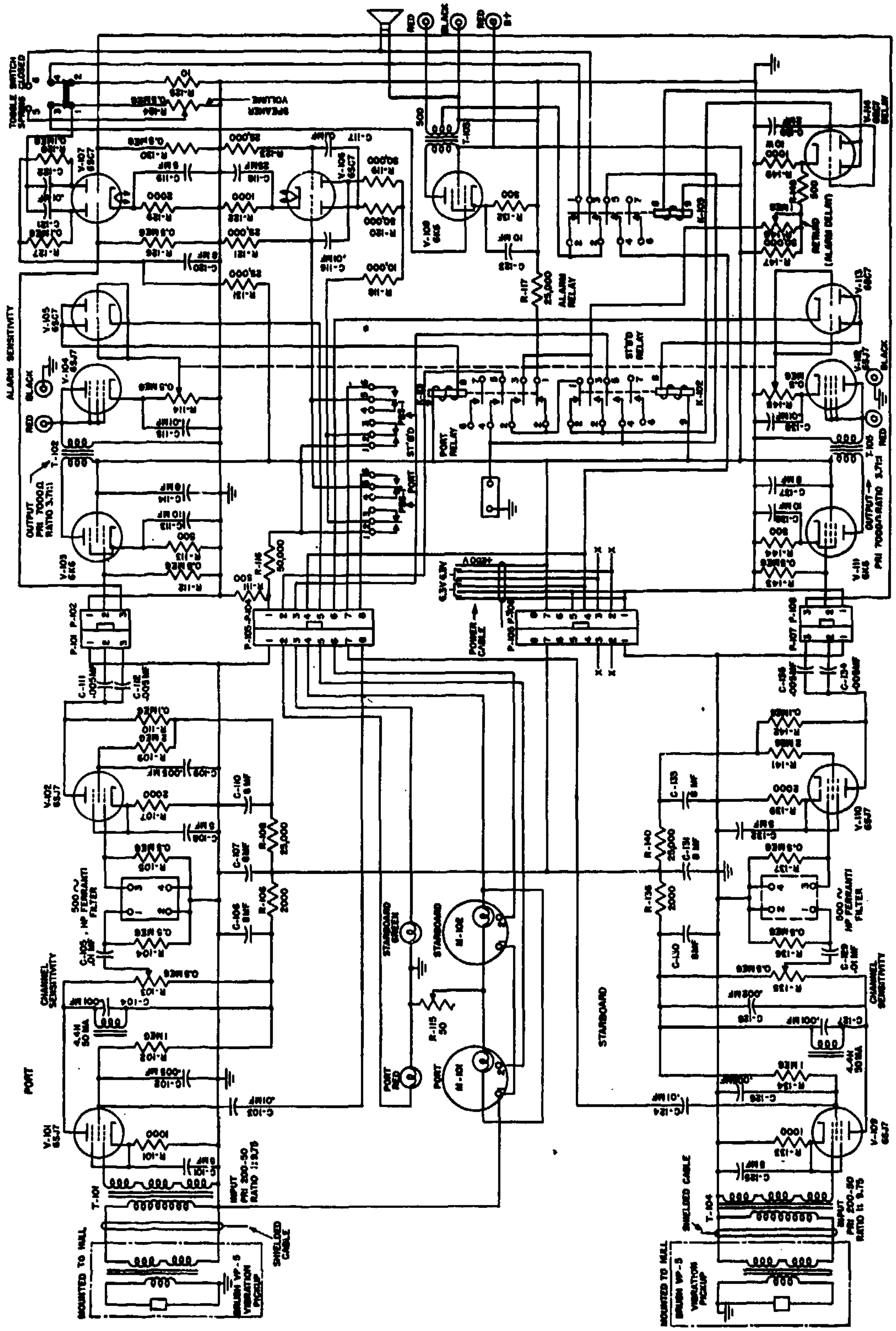


FIGURE 14. Circuit diagram of E-P torpedo detector.

of this relay completes the circuit to the alarm lamp corresponding to the particular channel receiving the signal and also connects the voice coil of the loudspeaker to the output transformer, T-103, to provide an audible alarm. The frequency response of the amplifier is shown in Figure 15.

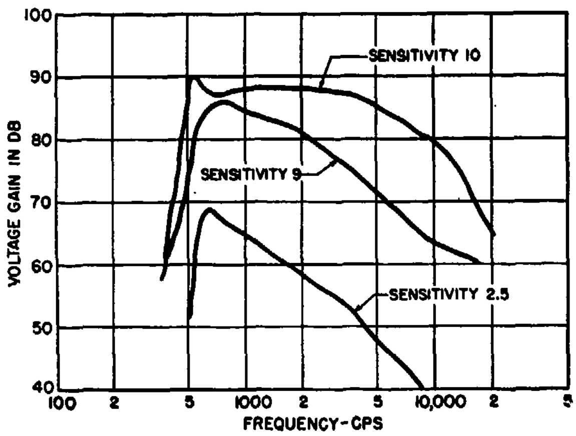


FIGURE 15. Frequency response characteristics of Electro-Protective amplifier for various channel sensitivities. Pickup unit and connecting cable are used as generator impedance.

The frequency and directional response characteristics of the pickup units were measured by projecting tones in the water from an underwater loudspeaker mounted on an auxiliary ship. The frequency response data for these units indicate that the effective response of this type of pickup (Figure 16), coupled to the ship's plates, lies in the region between about 1,500 and 3,000 c. The directional response data

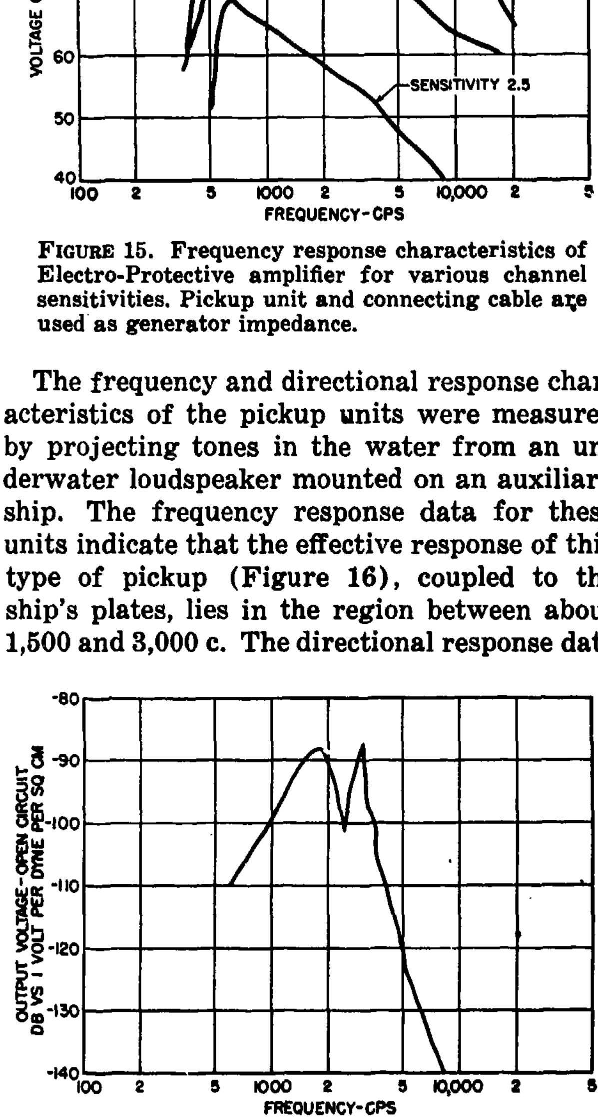


FIGURE 16. Average response of Electro-Protective pickup units as installed on SS *Colorado*.

indicate that the unit, as normally installed, covers a horizontal angle of about 150 degrees, from about 15 degrees off the bow to about 15 degrees forward of the stern.

Field Performance

Checks of the field performance of the torpedo detector were made at Newport, Rhode Island, under conditions closely simulating an actual attack. Six U. S. Mark XXIII (air-steam drive) torpedoes were fired at 45 knots from a distance of 2,000 to 3,000 yards with the tanker underway at approximately 17 knots and at a 24.5-foot draft.

With the ship underway, the detection ranges were found to vary from about 700 to 1,700 yards, corresponding to from 28 to 68 seconds of warning time. These observed ranges are in substantial agreement with those which would be anticipated on the basis of the separately measured torpedo and self-noise values and consideration of the alarm sensitivity settings used during the trials. From the range data on the Mark XXIII torpedo runs, it is possible to approximate the warning times to be expected with the E-P device for other types of torpedoes. For the case of the tanker running at approximately 17 knots and at a 24.5-foot draft, these probable warning times are given below.

Torpedo Type	Speed (knots)	Warning (seconds)	Detection Range (yards)
U. S. Mark XVIII (electric)	30	15–38	250–630
British Mark VIII (semidiesel)	45	20–48	500–1,200
German G-7-e (electric)	27	17–25	250–375

These calculated ranges are based on operation of the detector with the same alarm sensitivity settings as those used during the trial runs which were considerably higher than normally recommended.

Laboratory Tests

A disk sound recording of ship noise, taken through the E-P pickup on a tanker very similar to the one used for the field tests, and a recording (made utilizing a frequency band

corresponding to that of the E-P pickup) of the noise of an approaching Mark XXIII torpedo were played into the input of the torpedo detector both individually and simultaneously at various levels. By varying the relative amounts of torpedo and ship noise fed into the E-P equipment, and by changing the sensitivity and time delay settings, different conditions of operation were closely simulated. The results of this procedure indicated that a definite advantage in detection time could be obtained by keeping the sensitivity of the system as high as possible considering ship self-noise alone and setting the alarm time delay sufficiently long to minimize false alarms.

13.5 CONCLUSIONS

From a consideration of the results of the investigations carried out as outlined above, a number of broad conclusions were reached:

1. The sonic detection of submarine torpedoes at ranges up to the order of 2,000 yards from fast-moving merchant ships appears feasible under moderate sea conditions with either the rotating directional or the nondirectional type of detection system investigated. However, considerable care in installation, adjustment, and use is necessary if such ranges are to be consistently obtained. Careful monitoring of the nondirectional system is essential and the directional system requires a constant attentive watch.

2. Improvement in the performance of the nondirectional (E-P) system is necessary to make it satisfactory for routine use on fast merchant vessels. Specific suggestions for possible improvements to this device include: (a) the use of closer limits on the alarm sensitivity than are now recommended, (b) the use of a gain control on the speaker to permit better aural monitoring, (c) changes in the circuit which would improve its response to transient peaks, (d) redesign of the alarm circuit to provide actuation on modulation products instead of straight intensity discrimination and, (e) improvements to the pickup which would broaden its response to include the region between 500 c and 1,500 c. As emphasized in the reference, however, it is not believed that these suggested possibilities have been explored completely enough to justify their being considered as recommendations.

3. Tests of the particular rotating directional gear developed at the laboratory during these investigations were insufficient in themselves to determine completely the capabilities of this type of system. However, a consideration of the separately measured ship self-noise (with directional receivers) and the torpedo noise, coupled with the experience of the British with similar types of detection systems indicates that this type of detection equipment, in optimum adjustment, should give good results.

4. The advantages of the directional method over the nondirectional (actually, bidirectional) E-P system are: (1) accurate determination of target bearing and (2) possibly greater detection ranges. The disadvantages are: (1) greater complexity of the equipment required, (2) considerably greater installation problems, and (3) the necessity for constant monitoring.

FIGURE 17. Torpedo detection modification [TDM].

WCA-2 Torpedo Detection Modification[a]

The torpedo detection modification [TDM] to submarine supersonic equipment was developed to provide for the sonic detection of

[a] A similar modification employing *cathode-ray oscilloscope* [CRO] indication was incorporated in the *mine and torpedo detection* [MATD] equipment for WCA-2 gear and is described in Division 6, Volume 15.

torpedoes from submarines cruising on the surface, particularly to and from patrol areas. The modification is specifically applied to the submarine WCA-2 equipment but is adaptable to any similar type of gear. The equipment includes a slip-ring mechanism to enable continuous rotation of the projector at 12½ rpm, a speed faster than that used for normal listening or echo-ranging, and incorporates a recorder to give visual bearing indications. At a speed not exceeding 12 knots, submarines can usually detect and determine the relative bearing of enemy torpedoes at ranges of up to about 3,000 yards with this equipment. The torpedo detection modification was developed by CUDWR-NLL.

13.6 INTRODUCTION

It was believed that an acoustic system could be devised by means of which a submarine running on the surface could detect and determine the relative bearing of torpedoes fired at it in time to take successful evasive action. A survey of the characteristics of the transducers and amplifiers used with the current submarine supersonic gear indicated that this equipment, with suitable modifications to other components of the system, would be adaptable to use for torpedo detection.

Consequently a development program was undertaken, directed toward making the necessary modifications to provide an effective system as quickly as possible and toward evaluating the torpedo detection capabilities of such a system. As a result of this work, modifications have been evolved which are specifically applied to the WCA-2 sonar system,[7] but whose essential characteristics are applicable to any similar type of gear. Modifications include provisions for (1) continuous rotation of the projector in one direction, (2) rotation at a more rapid rate, and (3) incorporation of a chemical recorder to supplement aural listening and to provide a permanent record of the traces.

Tests of this system indicate that for submarine speeds not exceeding 12 knots, torpedo sounds can usually be detected, and the relative bearings determined, as far away as 3,000 yards. Later tests indicate the desirability of providing a streamline dome over the transducer to increase detection ranges and reduce mechanical strain on the training system at submarine speeds in excess of 10 or 12 knots.

13.7 SURVEY OF THE PROBLEM

A primary consideration in the development of acoustic equipment for the detection of torpedoes from submarines was to make such equipment available as quickly as possible. For this reason, and because the space for new equipment aboard modern submarines is very limited, it was necessary that maximum use be made of existing submarine sonar equipment.

To be most effective, a torpedo detection system for use on submarines should not only have as long a detection range as possible but, because the type of evasive action may depend considerably on the sector from which the attack is made, the system should also give an accurate indication of the torpedo's bearing.

Consideration of previous work, discussed in connection with the problem of sonic detection of torpedoes from merchant vessels, together with a knowledge of the characteristics of existing submarine supersonic listening and echo-ranging equipment, indicated that these requirements could be most readily met by modifications to this equipment. In the widely used WCA-2 sonar equipment, the QB projector is rotated at maximum speed of 4 rpm for normal listening and echo-ranging operations and, due to a cable connection, its rotation is restricted to approximately 2 turns in one direction.

Because of the need for detecting torpedoes as soon as possible after firing to allow the maximum time for evasive maneuvers, the rotational speed of the projector should be increased to reduce the 15-second interval between successive explorations at a given bearing and to aid the sound operator in differentiating between background noise and low-level signals from distant torpedoes. An upper limit on the rotational speed is determined by the necessity for the operator to correlate changes in sound level with the projector bearing, as indicated by the rotating pointer of the bearing repeater and by the mechanical

limitations of the training mechanism. A speed of 12½ rpm, providing successive observations on a given bearing approximately once every 5 seconds, satisfies all the requirements reasonably well. Because of the faster rotational speed of the projector and in order to simplify other features of the system, it was necessary to provide for continuous rotation in one direction by elimination of the cable connection and limit switches.

The background noise occurring on bearings abaft the beam increases rapidly with speed for submarine speeds in excess of 10 knots and this is believed due to turbulence or cavitation about the projector. For this reason and in order to reduce mechanical strain on the training mechanism, it is desirable to provide a streamline housing for the projector.

A change in the character or a very small change in the intensity of the received sound occurring as a rotating directional receiver passes rapidly through a particular bearing can usually be more readily detected aurally than by other means. For this reason and because experience may enable an operator to distinguish a difference between the noise from a torpedo and that from other types of targets, it is believed that aural listening provides the best primary means for long-range detection. It is desirable, however, to provide a recorder or other visual indicator as a supplement to aural monitoring. Such an indicator, although not usually so sensitive as the ear to signals very close to background level, is likely to yield more accurate bearing information and, in the case of a recorder, provides a permanent record which is useful in keeping track of any changes of target bearing between successive swings of the projector.

13.8 DEVELOPMENT

The development work on this problem was essentially that of determining the best and most expeditious means of modifying the WCA-2 equipment to meet the requirements of a torpedo detection system, as outlined in the preceding section, and of evaluating the performance of the system.

Continuous Rotation of Projector[8,9]

In order to make continuous rotation of the QB projector possible, it is necessary to provide electric connections to carry the received signals from the rotating to the stationary elements of the system without mechanically restricting rotation of the shaft. To accomplish this, the flexible cable connection to the projector assembly is replaced by a slip ring and collector braid mechanism.

The slip-ring assembly, shown in Figure 18, consists of two conductor rings, having outside

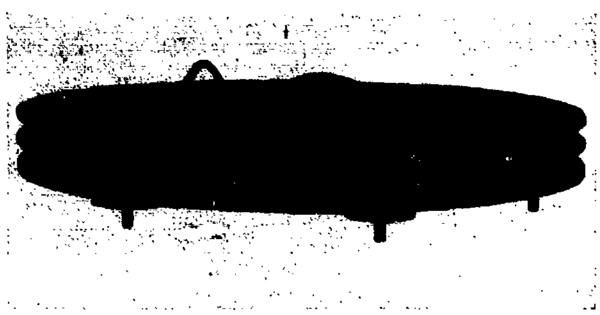


Figure 18. Slip-ring assembly.

diameters of 8⅜ inches, held in three hard-rubber holder rings. Each conductor and holder ring is split on a major diameter to permit installation around a continuous shaft, and the assembly is made rigid by staggering the joints between the split-ring sections. Each conductor ring is a lamination consisting of a rolled bronze channel, faced with a gold alloy overlay and sweat-soldered to a brass backing ring.

In the collector mechanism, two gold-plated copper braids are used to make electric contacts with the slip rings. These are secured to hooks fastened to stationary collector blocks which form a termination for a cable leading to other components of the system. The proper tension of the braids is maintained by means of helical springs. The slip ring and collector block installation is shown in Figure 19.

With elimination of the necessity for a cable connection to the projector assembly, the need for limit switches to restrict its rotation is removed, and performance of the system is im-

proved in normal listening or echo-ranging operations as well as for the torpedo detection application.

FIGURE 19. Slip ring and collector block installation.

INCREASED SPEED OF ROTATION

Preliminary tests conducted at sea indicated that the projector may be rotated at a speed of 12½ rpm without damage to the existing training motor due to overloading. Rotation at this speed is accomplished by replacing the existing 66-to-1 reduction gear with a 20-to-1 gear. In order to permit operation of the shaft at the original maximum of 4 rpm when the projector is used in normal listening or echo-ranging operations, the resistor values in the QB remote control unit (in the conning tower) are raised so that, on the first four contacts, the approximate shaft speeds are successively 1.0, 1.6, 2.4, and 4.0 rpm. A change from these normal speeds to the scanning speed of 12½ rpm is effected by using the fifth position of the remote control unit handle, in which position the resistances are out of the circuit. In the fifth position a spring latch, attached to the slewing control handle, fits over a stud fastened to the door of the control unit and holds the handle in place. This latch and stud also serve as a stop to prevent inadvertent use of the scanning speed during normal listening or echo-ranging operations.

When the local control unit (in the forward torpedo room) is used, provision is made for normal shaft speeds by the introduction of an additional 1,500 ohms in series with the MG generator field. This additional resistance is thrown into the circuit when the transfer switch, used for selecting local training control of the WCA-2 starboard (QB) or port (JK-QC) projectors, is in the starboard-train position. No provision is made to permit operation of the QB projector at scanning speeds when the system is controlled locally, but in an emergency this can be done by shorting out the added 1,500-ohm resistor and securing the control handle in its extreme right-hand position.

VISUAL INDICATOR

To provide a visual indicator as a supplement to aural detection of torpedo signals, a Sangamo sound range recorder, as described in Division 6, Chapter 6 of Volume 15, but modified to show bearings instead of ranges, is connected to the output of the WCA-2 heterodyne receiving amplifier. Modification of the recorder for this purpose is accomplished by arranging for the flyback of the recorder stylus to be controlled by a contactor on the projector shaft. A switch, keyed by this contactor, causes the stylus to return to the left margin of the recorder paper during the interval when the projector is scanning the sector from approximately 165 degrees to 195 degrees relative bearing, containing the submarine's screws. The stylus travels from left to right across the paper once for each revolution of the projector. When a target signal is being received, an increased flow of electric current from the stylus to a metal roller beneath the moist, chemically treated, recorder paper causes a darkening of the trace at the location on the paper corresponding to the relative bearing of the target. In Figure 20 the bearing recorder is shown as installed, together with other components of the system, in the conning tower.

13.9 TESTS

The torpedo detection modifications outlined in the preceding sections were carried out on the WCA-2 equipment of a fleet submarine and the installation was tested at sea under simulated operating conditions. Arrangements were made for a second submarine to fire a number of torpedoes at the boat containing the modified equipment while the latter boat was cruising on the surface at a speed of 8 knots. Each of these torpedoes, which were fired at ranges varying from about 3,000 yards to over 5,000

yards, were detected, both aurally and by the visual indicator, immediately after firing, and a continuous record of the bearing of each was obtained on the recorder from the time of firing until the torpedoes had passed under the submarine. A typical recorder tape for such a run is shown in Figure 21.

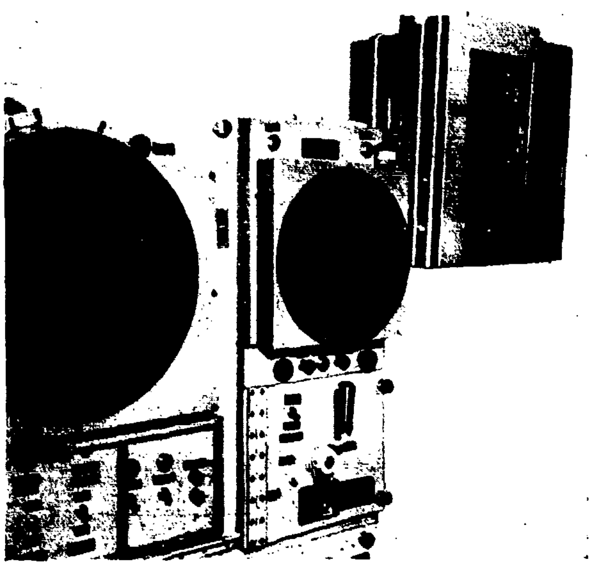


FIGURE 20. Bearing recorder and other system components.

Subsequent measurements of self-noise on this submarine at speeds of 8, 12, and 15 knots indicated that detection of torpedoes at ranges of 3,000 yards or greater can be expected only for ship speeds not exceeding 12 knots. At 15 knots the self-noise, particularly for bearings abaft the beam, was found to have increased sufficiently to reduce the expected detection ranges to about 1,500 yards. Later tests of a similar nature involving three other fleet submarines with modified WCA-2 equipments and conducted at ship speeds of 8 to 15 knots substantially confirmed these results.

Tests were also made to determine the loads on the training motor when the QB projector was rotated at the scanning speed of 12½ rpm with the submarine cruising on the surface and at 4 rpm with the boat underway submerged. It was determined that (1) the loads imposed on the motor under the conditions of the test did not exceed its full rated load, (2) a factor of safety is provided because the motor is designed to carry safely loads up to 175 per cent of full load, (3) the temperature rise of the equipment when operated continuously at 12½ rpm for 4 hours was well within safe limits. From these tests it was concluded that the training motor and the motor generator set would operate within safe limits under all anticipated conditions of operation after substitution of the 20-to-1 reduction gear for the original 66-to-1 gear.

Later operational reports from this boat and another submarine with similar modified WCA-2 equipment indicated some overheating of the training motor during continued rotation of the projector at 12½ rpm when the submarine was operating on the surface at speeds in excess of 10 knots. This overheating was not serious enough to disable the equipment, but because of concern about it and the undesirable limitation of detection ranges by high noise levels occurring on bearings abaft the beam at higher submarine speeds, it was decided to investigate the possible benefit of a streamline dome over the projector.

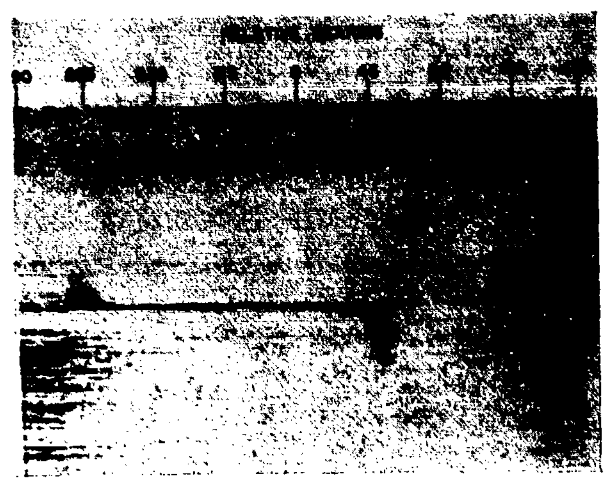


FIGURE 21. Typical torpedo trace as recorded aboard target submarine.

PROJECTOR WITH STREAMLINE DOME

Comprehensive tests were consequently made before and after installation of a 57-inch welded-on dome over the QB projector of another fleet submarine equipped with modified WCA-2 equipment. These tests were designed to determine the effects of the dome on self-noise (believed due to turbulence or cavitation

about the projector at the higher submarine speeds) and on mechanical strain on the training mechanism. Self-noise measurements and heat tests were made at submarine speeds ranging from 5.5 to 20 knots. As a result of these tests,[10,11] the following conclusions were reached.

1. At frequencies of 17, 24, and 30 kc, the installation of a streamline dome on the QB projector results in a consistent reduction in self-noise abaft the beam at all submarine speeds in excess of 6 knots.

2. In the forward sector (ahead of beam) use of the dome results in an increase in self-noise at the lower speeds. This effect is particularly apparent at a frequency of 30 kc where an increase of self-noise as high as 10 db occurs at a speed of 11 knots. At speeds of 15 to 16 knots and above, however, a progressive decrease in self-noise results, and the increase of self-noise introduced in the forward sector is not expected to reduce detection ranges sufficiently to impair the satisfactory and useful operation of the TDM.

3. Increases in detection ranges at ship speeds of 15 knots and greater, especially abaft the beam, are expected to improve the value of the TDM to submarines on war patrol.

4. Use of the dome makes it possible to hoist and lower the projector at all ship speeds.

5. Loads imposed on the training motor, with the submarine operated at 15 knots and the projector rotated at scanning speed, are reduced approximately 200 watts ($33\frac{1}{3}$ per cent) to about 50 per cent of rated full load by the use of a dome.

6. Loads imposed on the MG motor are also lower by approximately 200 watts, or about 20 per cent, with the dome installed.

7. With the loads encountered, temperature rise of the equipment after 5 hours of continuous operation at scanning speed and at ship speeds of 15 knots is well below the rated 40 C allowable rise either with or without the use of a dome.

8. Mechanical difficulties sometimes encountered, even at the normal 4-rpm searching speed, are largely eliminated through the use of a dome, provided the training equipment and the hoist-lower mechanism is in good condition at the time the dome is installed.

In addition to the self-noise and heat tests made with and without the dome, a series of torpedoes fired at this submarine while the boat was underway at speeds of 8 to 18 knots with the dome in place were detected. At submarine speeds of 12 to 15 knots, detection ranges varied from 1,160 to 2,580 yards. At the 15-knot speed several ranges of approximately 2,000 yards, corresponding to warning times of about 1.25 minutes for a 45-knot torpedo, were obtained. The sea was state 2 to 4, according to the scale given in *Instructions to Marine Meteorological Observers*, U. S. Department of Commerce, during these tests. For this reason the results are not considered to show conclusively the effect of the dome. The tests afforded an opportunity, however, for making phonograph recordings of torpedo sounds, as detected by the modified equipment, for subsequent use in training operators.

13.10 MODIFICATION KITS

Performance of the experimental torpedo detection modifications to WCA-2 equipment was judged by the Navy to be favorable enough to warrant production of kits in sufficient quantities to incorporate the modifications (exclusive of the dome) on virtually all fleet submarines.

13.11 CONCLUSIONS

As a result of the extensive tests of the torpedo detection modifications to WCA-2 equipment, it is believed that the gear will provide, under most operating conditions and at submarine speeds up to 12 knots, reasonably adequate warning of the approach of an enemy torpedo without the use of a dome over the projector. Because of the decreased detection ranges on bearings abaft the beam and the increased load on the training mechanism at speeds in excess of 10 or 12 knots, it is recommended that domes ultimately be supplied for installation over the QB projectors.

It is pointed out that in order to attain satisfactory performance, proper monitoring of the equipment is essential and the operator must give undivided attention to the indicators throughout the period of each watch.

Chapter 14

HARBOR PROTECTION SYSTEMS

BEFORE THE DEVELOPMENT of the *cable-connected hydrophone system* and the *anchored radio sono buoy* [ARSB], magnetic loop cables, minefields, submarine nets, and other fixed obstructions supplemented by armed patrol craft formed the protective barriers for inner harbor areas in wartime. Magnetic loop cables detected intruders at the seaward end of the harbor, but these cables only register the passage of any ferrous vessel crossing the loop and do not indicate actual position.

The cable-connected hydrophone system and the ARSB, discussed in this chapter, were proposed as alternate sonic methods of detecting and locating harbor intruders. Since the cable-connected hydrophones are tripod-mounted and require long transmission lines, they cannot be installed hurriedly or in deep water. The buoy, on the other hand, with its simple structure and radio transmission facilities, may be anchored relatively quickly in deep harbors.

Both hydrophone systems provide about the same detection range under good conditions, but the buoy suffers from instability in rough seas, inadequate low-frequency response, and higher background noise.

Cable-Connected Hydrophone System

The cable-connected hydrophone system was designed to detect and to determine the approximate location of enemy submarines approaching a harbor. The equipment consists of a series of tripod-mounted Brush C-37 crystal hydrophones regularly spaced at intervals of 1,000 yards across the harbor entrance. The hydrophones, each consisting of eight parallel-connected elements and a built-in step-down transformer, are connected by a submarine cable to a shore station where a switching mechanism and a sonic listening amplifier are provided. The switching mechanism, a rotary selector switch and relay circuit, automatically selects the separate hydrophones for listening, allowing the operator to monitor the various units successively. A timing circuit comprising motor-driven cams enables the operator to adjust the listening time intervals to 2, 3, 5, 7½, or 10 seconds. The listening amplifier has a frequency characteristic uniform within 3 db over the range 70 c to 12,000 c. High-pass filters with cutoff frequencies of 600 c, 1,200 c, and 2,400 c are available. Either headphones or loudspeaker may be used for listening with this system. Development work on the system was done on an advisory basis with the Bureau of Ships by the CUDWR-NLL, with the close cooperation of BTL.

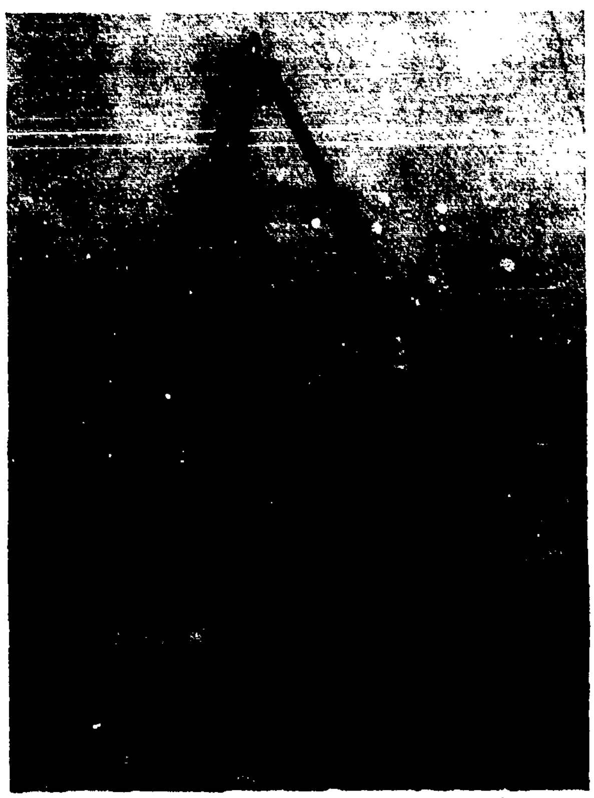


FIGURE 1. Cable-connected hydrophone and tripod assembly.

14.1 INTRODUCTION

The proposal for a system of anchored cable-connected hydrophones for harbor protection led to the design and installation of two cables. The first of these, laid near the entrance to Block Island Sound, was an experimental system used primarily to determine the requirements for this application. The second system, at Cape Henry, designed on the basis of data gathered with the first, served as a model for further military installations.

The Cape Henry installation consisted of 14 tripod-mounted hydrophones spaced 1,000 yards apart along an armored cable beginning at a point about 5 miles from shore and terminating in a shore listening station. Provision was made for shore-controlled automatic switching between the hydrophones and for listening by means of either headphones or a loudspeaker. Although some initial trouble developed in the system from hum pickup and minor mechanical failures, these difficulties were ultimately corrected and satisfactory performance of the installation was obtained. Listening ranges of over 7,000 yards were attained for surface ships. Determination of approximate target position was possible by comparison of the relative intensities of signals received on two or more of the spaced hydrophones.

14.2 DESIGN PROBLEMS

A number of sonic methods of detection have been proposed to supplement the loop cables by providing more accurate information concerning the location of vessels. Among these, echo-ranging stations located on the ocean floor, rotatable binaural listening systems, arrays of ARSB's, discussed later in the chapter, and systems of cable-connected hydrophones received serious consideration. Although more accurate information can be obtained with echo-ranging or binaural systems than with nondirectional buoys or the cable-connected hydrophone system, serious mechanical difficulties are encountered in providing the complicated underwater mechanisms necessary for the former. Cable-connected listening hydrophones appeared to offer the best possibilities for use as a secondary detection system for harbor protection.

The use of cable-connected hydrophones requires unit spacing to insure overlapping of effective detection areas and careful selection of locations where favorable listening conditions exist in the seaward direction and along the cable. Ambient noise measurements and underwater-listening-condition surveys in harbors have established certain facts that restrict the choice of locations. These studies have shown that transmission of sound is poor over steep submarine valleys or shoal spots and over very muddy bottoms and that certain localities are unsuited because of excessive noise levels which may result from any of several sources. Among these are (1) noise-producing fish and other forms of marine life, notably croakers and snapping shrimp, (2) bottoms composed of loose stones, especially where strong tides or heavy seas cause frequent shifting, and (3) manufacturing, shipbuilding, and other similar activities on or near shore.

The character of the underwater sound received from a ship provides an experienced listener with considerable information concerning the type and speed of the vessel. When a number of spaced hydrophones are available for successive listening, the relative magnitude of the sound intensity received by two or more loose stones, especially where strong tides or crease in intensity provide additional information concerning the vessel's location and direction of travel.

In order to make full use of these potential sources of information, the cable-connected hydrophone system should provide high-quality reproduction at the listening station, well-balanced sensitivity among the various channels, and freedom from noise interference. These requirements necessitate (1) hydrophones having reasonably flat frequency response characteristics and uniform sensitivity high enough to insure that unavoidable water background noise, not inherent cable noise, limits the range, (2) a cable whose transmission characteristics do not seriously alter the character or relative levels of the acoustic signals and which is not exposed to serious electric interference, (3) a high-fidelity amplifier and reproducer, and (4) shore-controlled switching between the outputs of the individual hydrophones.

In addition, because selective listening may sometimes be desirable in discriminating against certain types of ambient noise, suitable filters should be provided in the amplifier. The sonic noise from croakers and most fish [1,2] lies largely in the frequency range below 2 kc, while that from snapping shrimp is almost entirely above 1 kc.[3] Provision of a high-pass filter with a cutoff at 2 kc, therefore, permits listening to ship sounds in areas where fish are prevalent while a low-pass filter having a 1-kc cutoff discriminates against the noise of snapping shrimp.

14.3 THE BLOCK ISLAND EXPERIMENTAL CABLE SYSTEM

OBJECTIVES

Design and installation of an experimental system in Block Island Sound [4] were undertaken as a means of obtaining information on a number of questions pertinent to the successful operation of a cable-connected hydrophone system. It was desired to (1) make tests to determine the usefulness of cable-connected hydrophone listening under operating conditions, (2) obtain information that would indicate the most suitable types of hydrophones, amplifiers, and headphones or loudspeaker, (3) determine the best available methods of installation for the hydrophones and other underwater components, (4) investigate designs for underwater cable junction boxes and the reliability of vacuum-type relays for use in such boxes, (5) determine the electric loading of the cable necessary for optimum transmission characteristics, and (6) obtain sufficient operating experience to enable recommendations for methods of observation.

In addition to the information expected from the experimental cable installation, underwater sound surveys were undertaken to determine listening conditions in several areas proposed for tactical installations.

DESCRIPTION

The Block Island hydrophone system utilized two armored quadded cables 8,000 and 10,000 yards long. Each cable was spliced at 1,000-yard intervals and the larger cable was provided with loading coils at each splice. Four hydrophone stations, at respective distances of 7,000, 8,000, 9,000, and 10,000 yards from shore, were served by the two cables. A single tripod provided at each station served as a mounting for two different types of hydrophones. Terminal boxes mounted on each tripod contained the hydrophone-to-cable splices, coupling condensers, and glass-enclosed contact magnetic relays used to switch from one hydrophone to another.

Cable Loading. The loading coils used at 1,000-yard intervals in the longer cable were of the "wedding ring" type (Western Electric Type No. 0-162490), designed to load the cable for a nominal cutoff frequency of 15,700 c and an effective transmission band of 12,500 c. "Straight-through" and Y-type nonwatertight splice cases were used to permit continuity in the mechanical protection of the cable. Each conductor was made watertight individually at the splices by means of several layers of DR tape.

Tripods. The hydrophone tripods, 8 feet high and 7 feet wide at the base, were constructed of 1-inch steel tubing set into 100-pound concrete blocks at the base of each leg. Six hundred-foot lateral cables connecting the hydrophones to the main cables through Y-splices permitted the tripods to be raised separately for maintenance purposes. All flexible parts were secured to the tripods to prevent water currents from causing mechanical noise.

Hydrophones. The eight vertically-mounted hydrophones installed on the four tripods comprised two 4-foot and two 6-foot magnetostriction units and three 16-inch Brush C-23 and one 54-inch Brush C-37 crystal units. Two units were served by each of the four pairs of wires provided in the two main cables. Selection of the desired hydrophone of the two on each pair was accomplished by actuation of the relays at the tripods by compositing (CX) circuits similar to those used in standard telephone practice.

Shore Receiver. At the shore station a preamplifier, intermediate amplifier, and power amplifier were utilized to provide for listening by means of a 12-inch speaker or high-quality headphones.

Hydrophones. Extensive tests were conducted to determine the effectiveness of this type of hydrophone installation as an integral part of a harbor-defense system and to obtain the information necessary to evaluate the characteristics, performance, and reliability of the various system components. Listening tests, in which submarines were maneuvered in the hydrophone cable area, resulted in minimum detection ranges of from 1,000 to 2,000 yards with the boats operating at 80 rpm (4 knots) at periscope depth. Under more extreme evasive conditions, with the boats operating submerged at creeping speeds of 2 knots (40 rpm), detection was still possible, principally as a result of the sounds from various auxiliary machinery within the boats. These tests served also as a means of comparing the performance of the various types of hydrophones. It was found that in this application the 54-inch long Brush C-37 crystal unit gave the best balance between sensitivity, frequency characteristic, and directional exclusion of surface noise.

Recorders. During routine listening tests extending over a period of several months, an investigation was made of graphic recorders and phonograph recorders as detection aids to supplement listening. It was found that in some cases small changes of level could be detected more readily with a linear graphic level recorder (an Esterline-Angus recording ammeter with a linear rectifier) than by ear, although the listening differential generally favors aural methods of detecting below-background noises, particularly when discrete frequency components are present. The graphic recorder, furnishing a permanent time record of ship movements, also makes possible the identification of various types of vessels from their "signature" on the tape. For these reasons it was considered a useful addition to the hydrophone monitoring equipment. Tests also showed that a magnetic-tape loop recorder is advantageous for listening repetitively to sounds of a transient nature.

Amplifiers. Various types of commercially available amplifiers were tried out in a series of tests on the Block Island experimental system,[4] but no single amplifier was found which adequately met all the requirements for a unit to be used with a tactical installation. Consequently, a special amplifier was designed for this purpose.

Cable. Calculations of the impedance and transmission characteristics of the Block Island hydrophone cable, based on constants determined by measurements on a sample section, showed that the estimated improvement of transmission by loading could not be realized due to a large increase in leakage conductance of the cable after prolonged submergence in sea water.

Maximum Ranges. Under normal listening conditions large surface ships could be heard at ranges of 8 to 15 miles and submarines on normal practice maneuvers could at times be heard as far away as 8 miles. The character or severity of the temperature gradient conditions in the water apparently had negligible effect on the listening conditions, presumably because the shallow water and hard bottom in the area provided multiple-path sound transmission.

Comparison with ARSB. To compare the performance of the cable-connected hydrophone system with that of the ARSB, a buoy was anchored in the vicinity of the hydrophone cable and provision made for alternate listening with the two systems. It was concluded that (1) the ARSB and the cable-connected hydrophones had about the same detection range under good conditions; (2) the deficiencies of l-f response of the buoy hydrophone (Brush C-23) made identification of the various types of vessels difficult; (3) the buoy, having its hydrophone closer to the surface, picked up more background noise; and (4) tangling of the buoy's hydrophone and battery cables caused some rubber squeaks particularly in a fast-running tide.

14.4 THE CAPE HENRY CABLE-CONNECTED HYDROPHONE INSTALLATION

The component parts and methods of installation used in the Cape Henry cable-connected hydrophone system, a tactical installation at the entrance to Chesapeake Bay, were chosen largely on the basis of the experience gained in the operation and testing of the Block Island system.

The Cape Henry system incorporates 14 Brush C-37 hydrophones mounted vertically on tripods spaced 1,000 yards apart and connected to a shore listening station by means of a 16-conductor armored cable having a central quad of two listening pairs. Adjacent hydrophones are connected to alternate listening pairs while switching between hydrophones is accomplished by means of relays controlled by the 12 outer conductors of the hydrophone cable. Three hundred-foot, four-conductor, lateral cables are used to connect each hydrophone to the main cable at 1,000-yard splice intervals. Waterproof splice boxes housing 6-inch loading coils are provided at each main cable splice. Terminal boxes, containing the relays, attenuating pads, and the connections between the individual hydrophone cables and the lateral cables, are mounted on the tripods. A schematic diagram of the cable layout is shown in Figure 2.

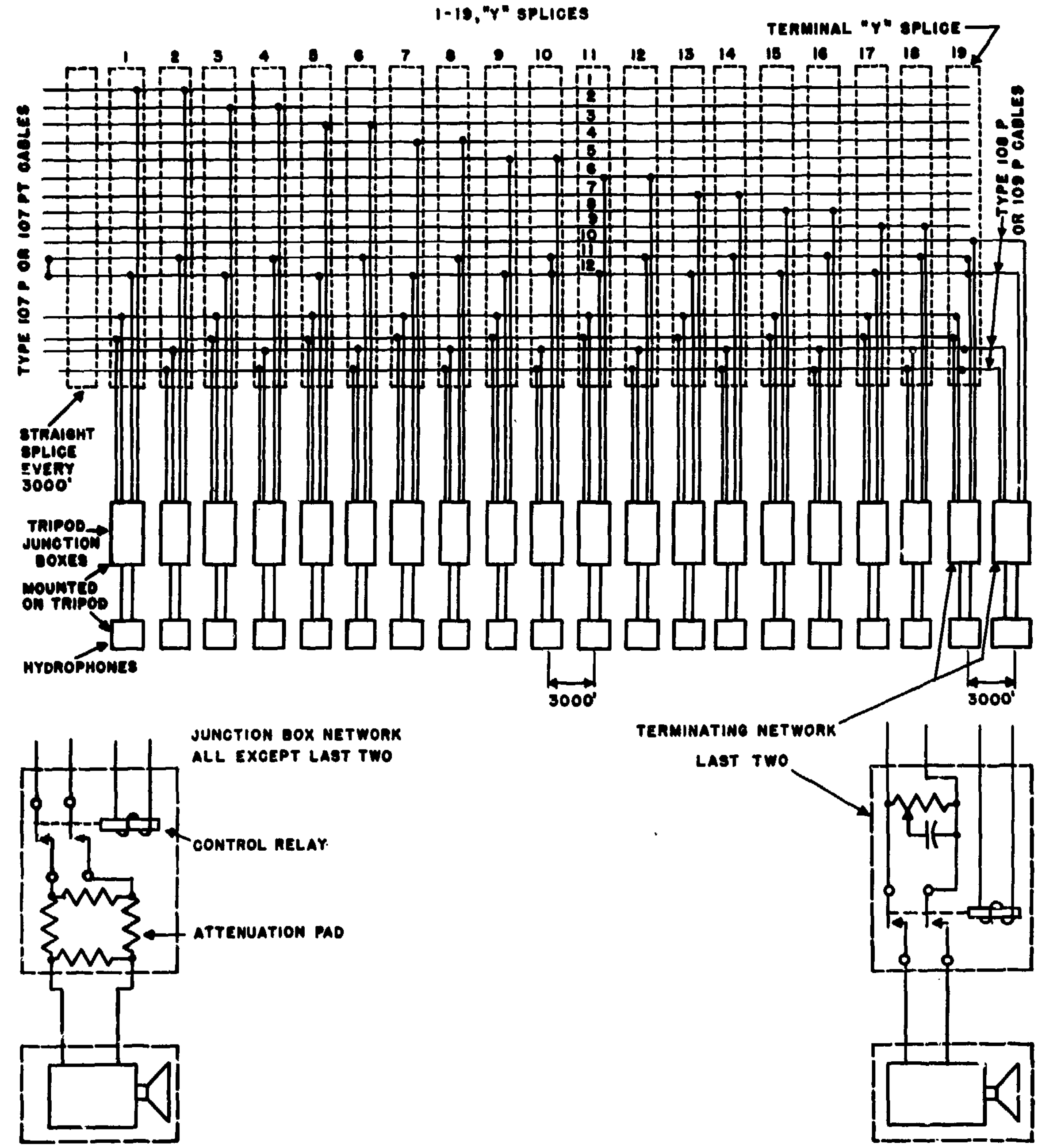


FIGURE 2. Schematic diagram of typical cable-connected hydrophone system.

Cables. The conducting portion of the main cable (Simplex Wire and Cable Company, cable Type No. 107) consists of a center quad of 4 No. 14, 7-strand, tinned copper wires and a concentric ring of 12 No. 16, 7-strand (4 copper, 3 steel) wires. Rubber and thermoplastic insulation is provided and mechanical protection is furnished by 33 strands of No. 12 steel wire and an outer sheath of impregnated jute. The lateral cable (Simplex Wire and Cable Company, Type No. 108) is similar to the main cable, but its conductors consist of only the center quad, one pair carrying the signal and the other serving the relay control circuit. Figures 3 and 4 show sectional views of the two cables and include tables of their physical properties.

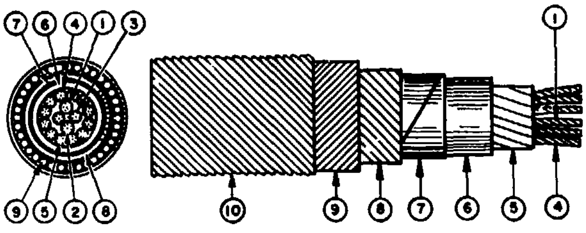


FIGURE 3. Main cable construction.

Splice Boxes. The waterproof splice boxes are built to withstand high water pressure and provide continuity of the outer cable protection. Circular end plates, 6 inches in diameter, contain standard rubber-washer type glands and are rigidly connected to each other by steel straps. The outer covering is a cylindrical steel case. Cable-armor clamps are provided at each end (Figure 5). Although the cases are designed to be waterproof in themselves, additional protection is provided by waterproofing each individual conductor splice with DR tape and by filling the case with a low-melting-point potting compound. On test, the case alone has withstood a hydrostatic pressure of over 1,000 psi.

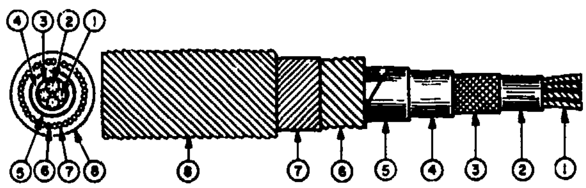


FIGURE 4. Lateral cable construction.

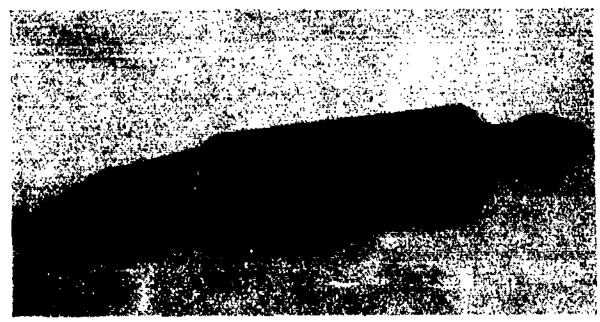


FIGURE 5. Straight-through splice case.

Relays. A conventional type of relay was selected for switching between hydrophones, as it was believed that the reliability of the glass-enclosed vacuum-contact relays used in the Block Island installation was not sufficiently established by adequate field trials. The unit selected (Western Electric U.A. Type D163523) has four sets of normally open contacts and operates on a current of from 6 to 50 milliamperes with a maximum power dissipation of 7 watts. The relays are enclosed in steel boxes tested to withstand a hydrostatic pressure of 100 psi.

Attenuating Networks. In order to equalize the cable transmission losses from the different hydrophones, attenuating networks are provided in series with each hydrophone except the most remote on each circuit. The pads are installed in the terminal boxes on the tripods and are connected between the relay and the hydrophone so that they are in the circuit only when that hydrophone is in use. The transmission loss of the pads is such as to equalize the general transmission level of the signals at the receiving end, but it does not correct for differences in the transmission-frequency characteristic of different lengths of cable.

Terminating Networks. The seaward end of the cable is terminated in a network which matches the cable impedance in order to prevent serious reflections on the cable and to

make the bridging losses uniform at each point where the laterals connect to the main cable. Full-coil impedance is simulated by a 325-ohm resistance bridged by a 0.04-μf condenser and connected to the circuit beyond the final loading coil. Use of this termination prevents resonances which would otherwise cause large variations with frequency in the bridging losses, depending on the position of the particular hydrophone in use.

Tripods. The tripods used in the Cape Henry installation are similar to those used at Block Island but are constructed of extra heavy 1½-inch steel pipe. Heavy concrete blocks at the bottom of each leg make the total weight of the tripod, hydrophone, and terminal box about 700 pounds. A 600-foot 4-inch manila line, chain-weighted at the end, provides a means of hoisting the tripod without the necessity of dragging for the lateral cable. A complete hydrophone-and-tripod assembly is shown in Figure 1.

Hydrophones. The Brush C-37 hydrophone, which was selected on the basis of the tests made at Block Island, is a Rochelle salt crystal unit having eight parallel-connected crystal elements and a built-in, step-down transformer. The crystals are encased in an oil-filled cylindrical rubber container 55 inches long and 2½ inches in diameter. Reinforcement inside the rubber covering provides for clamping of the unit at two points. Figure 6 shows the average measured sensitivity of five C-37 hydrophones

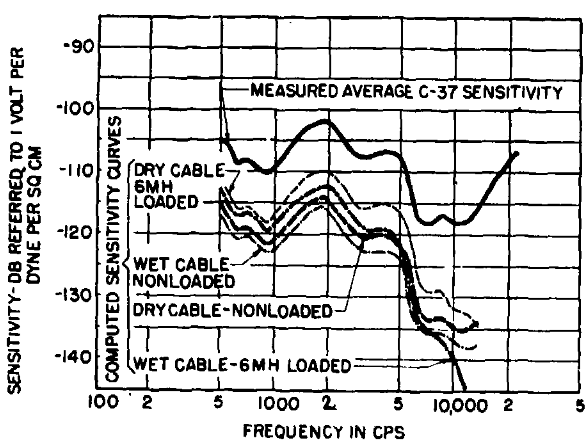


FIGURE 6. Measured sensitivity of C-37 hydrophone and computed "equivalent sensitivity" with 60,000 feet of cable.

without cable and the computed equivalent sensitivity[a] of this unit when connected to twenty 3,000-foot lengths of cable with the cable wet and dry, loaded and unloaded.

Listening Amplifier. The amplifier (U. S. Navy CDI-50123; uses rectifier CDI-20186) used with the Cape Henry installation is a production model of a unit designed in accordance with requirements indicated by the Block Island installation. It permits either headphone or loudspeaker listening. The input impedance is 200 ohms balanced to ground, and 130 db of gain with a maximum power output of 1 watt at 5 per cent total harmonic distortion is provided. Normal frequency response is flat within 3 db between 70 and 12,000 c, although high-pass filters with cutoff frequencies of 600, 1,200, and 2,400 c are available.

Switching Circuit. A simplified schematic diagram of the hydrophone switching equipment is shown in Figure 7. This equipment automatically switches the individual hydrophones of the cable system into the listening circuit allowing the operator to listen successively to the various units and spend a selectable interval of time on each. Listening intervals of 2, 3, 5, 7½, or 10 seconds are made available on each hydrophone by means of a motor-driven cam-switching mechanism. Provisions are made both for repeating the automatic selection of desired hydrophones and for disabling the automatic timing and selector circuits to permit extended listening on any particular hydrophone when desired. Switching transients are suppressed automatically by placing a short circuit momentarily across the listening amplifier output.

Cable Transmission Characteristics. Values of the attenuation and phase shift per nautical mile of the main cable with and without loading, as computed from constants determined by measurements on sample lengths, are shown in Figure 8. Although submergence of the cable in sea water for a period of several months appears from these data to have little effect on

[a] The equivalent sensitivity is the open-circuit voltage in decibels referred to 1 volt appearing across an ideal-characteristic impedance terminating network when the hydrophone is subjected to a sound pressure of 1 dyne per sq cm and the hydrophone is connected to the terminating network through the length of cable with which it is to be operated.

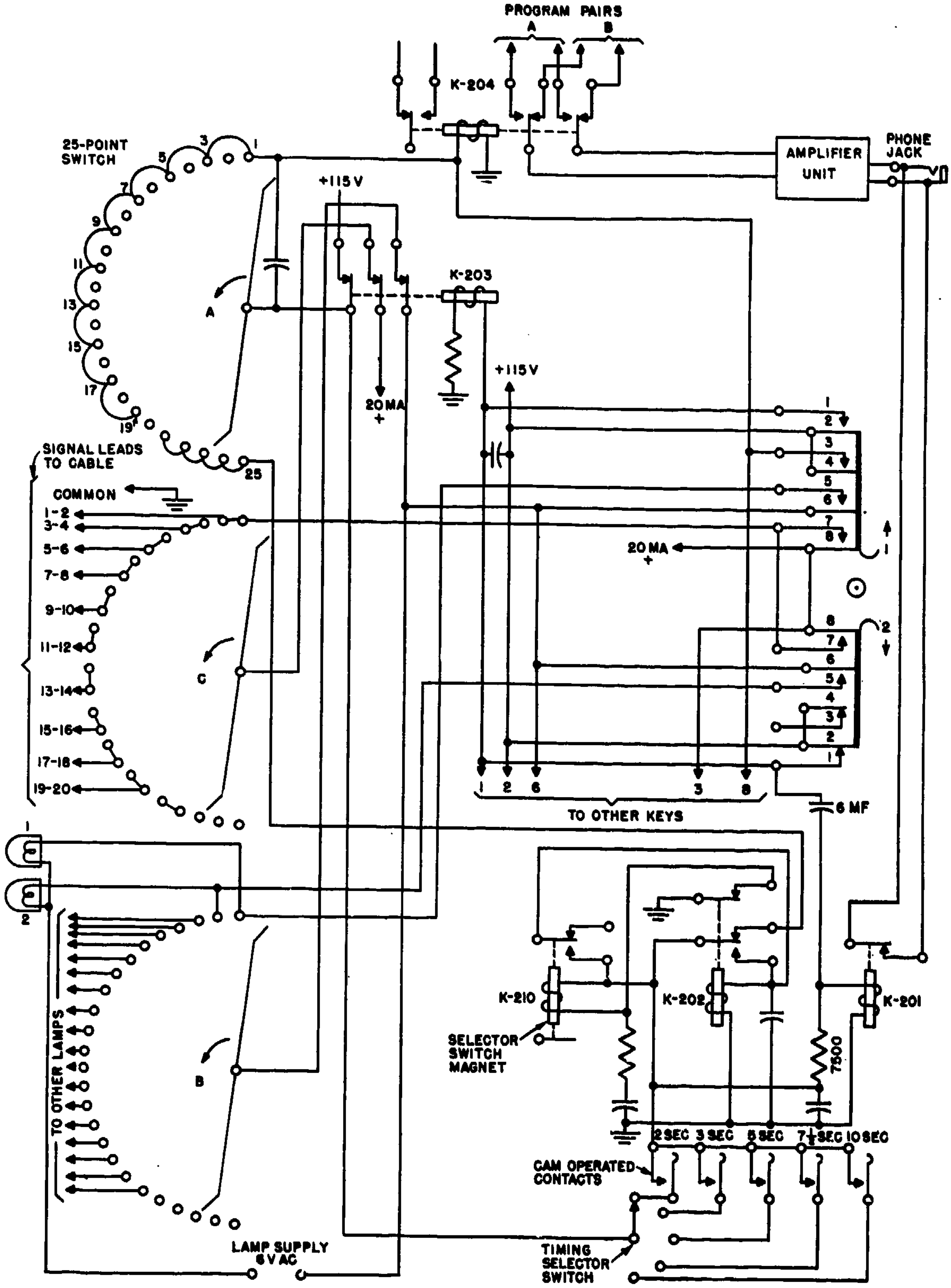


FIGURE 7. Schematic diagram of switching unit.

the phase shift, the attenuation per unit of length is increased appreciably particularly at the higher frequencies. Actual tests on an 8-mile length of dry cable just before laying indicated losses which are in reasonable agree-

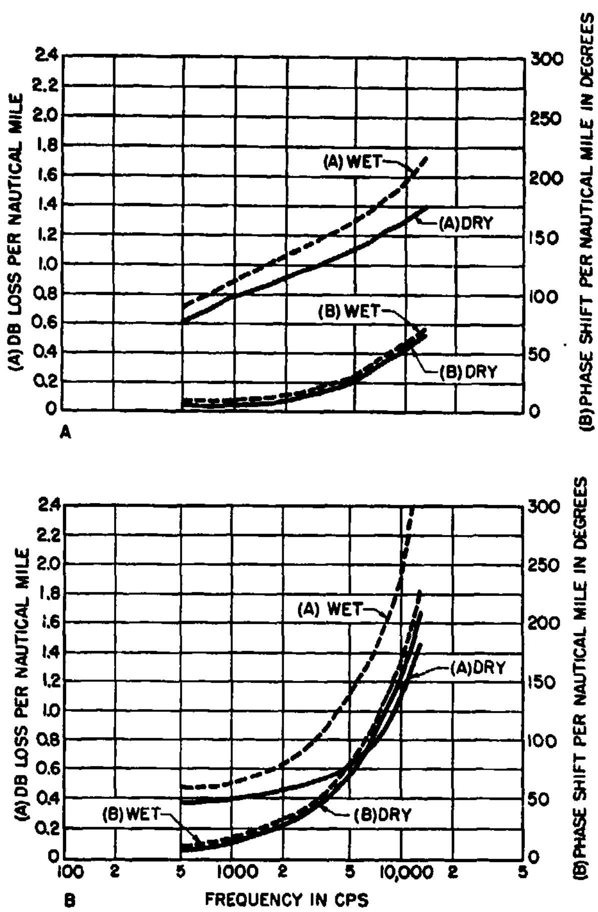


FIGURE 8. Computed propagation constants of cable: (A) nonloaded cable; (B) cable with 6 mh per 1,000 yards loading.

ment with the calculated values. Measurements made at this time also indicated that the cross talk between the listening pairs varies from −59 db at 1 kc to −49 db at 10 kc.

PERFORMANCE

During preliminary tests, considerable a-c hum, originating in a 2,000-yard section of cable between the listening post and the beach, was present. This section of cable was paralleled for a considerable distance by a 2,300-volt 3-phase power line and lower voltage secondaries.

Although the use of the 600-cycle high-pass filter was effective as a temporary expedient, it was felt desirable to increase the signal-to-noise ratio of the incoming signal by installing repeater amplifiers where the cable emerges from the sea. These amplifiers, housed in a weatherproof ventilated metal cabinet, are supplied with d-c power over three spare control conductors of the cable from the listening post. They have a substantially flat frequency response between 100 and 12,000 c, and a gain of approximately 40 db.

In addition to the hum picked up directly by the listening conductors, it was found that the control conductors in the shore section of the cable also picked up hum. As these hum currents caused interference with the listening circuits, low-pass filters for each control wire were installed on the seaward side.

After these and other lesser difficulties were corrected, the system performed satisfactorily. No significant interference has been experienced from background noise of acoustic origin other than normal water background noise, and consistent detection ranges of over 7,000 yards have been attained on surface ships.

14.5 RECOMMENDATIONS

A number of means of improving or simplifying the performance of cable-connected hydrophone systems have been devised since construction of the Cape Henry system.

Hydrophones. A 5-foot long, permanent-magnet magnetostriction hydrophone, NL-124 (CQA-51074),[b] offers several advantages over the Brush C-37 unit: (1) Its lower impedance eliminates the necessity of a line transformer and is virtually independent of temperature. (2) Its sensitivity is higher. (3) It is capable of withstanding the more severe shock pressures of nearby depth charge or mine explosions. (4) Its construction makes it easy to assemble. (This unit is capable of operation under hydrostatic pressures up to 500 psi.) Installed in a vertical position on a tripod, this hydrophone discriminates against sound originating directly above and when equipped with a suitable baffle it may be made essentially uni-

[b] Calibration of this unit is given in Chapter 6, Volume 11, Division 6.

directional. This permits discrimination against ship sounds within a busy harbor, or against surf noise, while at the same time retaining normal response in the seaward direction.

Cable Loading. After the effects of prolonged submergence on the leakage conductance of the cable were determined, the benefits from loading were found to be much less than originally expected. For this reason it was decided to recommend the omission of loading on any future cable-connected hydrophone systems using this type cable. It is expected that the use of the nonloaded cable will result in (1) greater simplicity and lower cost, (2) improvement of circuit balance with consequent reduction of noise pickup, (3) reduction of the effect of cable leakage upon attenuation, (4) improved impedance match between hydrophones and cable, (5) lower thermal noise from the cable, and (6) greater reliability. In addition, the use of nonloaded cable enables the future transmission of supersonic signals in the event this should appear desirable inasmuch as the h-f cutoff introduced by loading would make such transmission impossible.

Hydrophone Matching Networks. The optimum condition of matching between the hydrophone and cable impedances occurs when the hydrophone impedance is the conjugate of that of the cable. It is possible, therefore, to produce some improvement in the transmission of the higher frequencies by providing a transformer to step up the hydrophone impedance together with a shunting condenser to nullify the positive reactance of the hydrophone at a selected frequency. However, the slight increase in transmission efficiency obtainable by the use of such matching networks does not warrant their use on the lengths of cable usually necessary for harbor protection systems, as the acoustic background noise is generally well above the thermal noise on such lengths of cable. On unusually long cables, where thermal noise approaches the water noise level, it may be of advantage to provide matching networks.

Splicing Procedure. On the Block Island and Cape Henry cables, straight color-to-color splices were used between the listening conductors in the various sections. By making capacity-unbalance tests and splicing the conductors, regardless of color, so as to equalize the capacity to ground, the circuit balance can be improved and the susceptibility to inductive interference reduced.

Equalization of Signal Levels. With fixed attenuation pads installed at the tripods to adjust the levels of the signals from the various hydrophones on the Cape Henry system, no provision is made for compensating for possible changes of hydrophone sensitivity with time. An alternative method of equalizing the levels is recommended in which the attenuation pads would be installed at the listening station and selected by additional arcs on the rotary selector switch or by means of relays controlled by the existing selector mechanism. This type of equalization could be employed at the amplifier output and the pads made variable by means of screwdriver adjustments.

Timing Circuit. In order to provide variable listening intervals without the use of a series of motor-driven cams, an electronic timing circuit employing a gas-filled, cold cathode tube is suggested. Such a circuit, in addition to eliminating the cumbersome motor and cam mechanism, would provide for continuously variable intervals instead of the predetermined intervals necessitated by the cam arrangement.

Relay Switching Circuit. Another arrangement, consisting of a relay chain circuit instead of a rotary selector switch, has been successfully tested. Similar to the counting circuits employed in standard telephone service, it provides automatic and manual selection of individual hydrophones by means of keys.

The Anchored Radio Sono Buoy [ARSB]

The anchored radio sono buoy [ARSB] is a device which is anchored in a harbor to pick up enemy submarine sounds and transmit them by radio to shore receiving stations. The final model [JM-1] consists of two buoys connected by cables. One buoy contains a transmitter with maximum deviation to 75 kc, a small nondirectional hydrophone suspended below on a cable, and a half-wave antenna. The other buoy houses a removable 20-day dry-cell battery power supply and the anchor. Important design

features of the equipment are the use of pre-emphasis of high frequencies, high audio gain, acoustic padding inside the transmitter buoy to reduce microphonics, heater-type tubes, and a quarter-wave ship antenna with ground plane. The original ARSB, known as the JM buoy, was developed by the NRL for the Bureau of Ships. Later NDRC contributions were in co-operation with the Brush Development Company in the selection of the hydrophone, and generally small but important suggestions for improvement of the early production models, the development of methods of anchoring and managing the cables to eliminate noise and tangling, and assistance in personnel training.

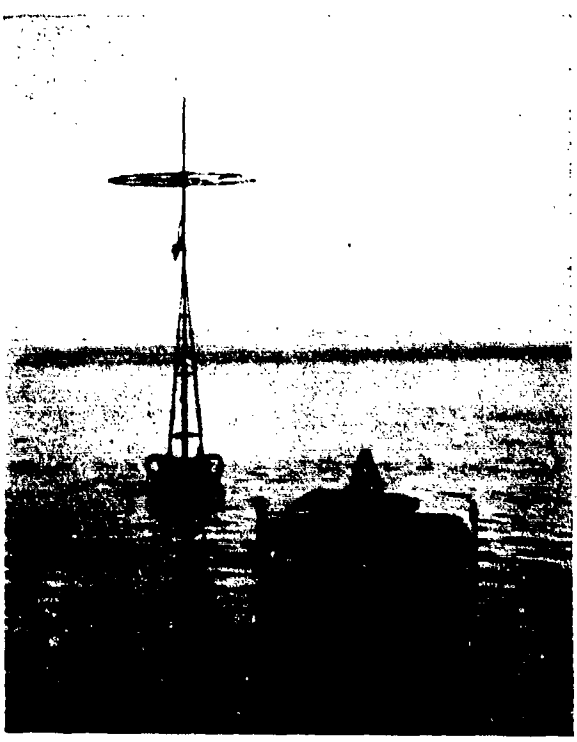


FIGURE 9. The JM-1 anchored radio sono buoy.

14.6 INTRODUCTION

The ARSB is reserved for use in deep water where laying of cables is not feasible, and for auxiliary or emergency use at advanced bases where the expenditure of time, material, and effort needed for a cable-connected hydrophone system would not be justified. Underwater sounds, picked up by the hydrophone, are amplified and impressed by means of FM on a radio carrier wave. Trained listeners at a near-by shore listening post can then maintain a continuous watch on ship sounds in the area.

The final model, JM-1, operated satisfactorily at an 8-mile radio range and equaled the cable-connected system in acoustic performance under favorable weather conditions. The buoy itself could not withstand severe storms. Suggestions for further research and development propose incorporation of all components in one streamlined buoy and inclusion of a device to enable alternative directional and nondirectional use of the hydrophone.

14.7 DEVELOPMENT

14.7.1 The JM Buoy

The JM buoy assembly, shown in Figure 10, consisted of two buoys, one a transmitter buoy from which a hydrophone was suspended, and a separate anchor buoy to prevent cable fouling. The electric equipment consisted mainly of a dry-cell power supply, a medium-gain audio amplifier, an FM carrier wave system, and a half-wave antenna.

A large number of field tests were carried out in cooperation with the Brush Development Company to determine the most suitable hydrophone available and the optimum coupling of the hydrophone to the amplifier. Under different weather conditions, different types of hydrophones gave the best performance. However, the small C-23 Brush hydrophone was recommended as giving the most satisfactory all-round performance.

It might be presumed that a long hydrophone, one with directional characteristics to discriminate against surface sounds, would be especially suited to this device. However, when suspended in the usual way from an anchored buoy, the hydrophone may be deflected from its vertical position by a water current of any appreciable magnitude. A long hydrophone thereby defeats its own purpose.

The *automatic volume control* [AVC] incorporated in the JM audio amplifier was found to reduce the sensitivity of the buoy by about

10 db for moderate signal levels. It was accordingly disconnected in all JM transmitters.

Further tests indicated that the buoy was as efficient as could be expected with the filament-type tubes available. However, it was believed that considerably improved performance might be obtained with other tubes.

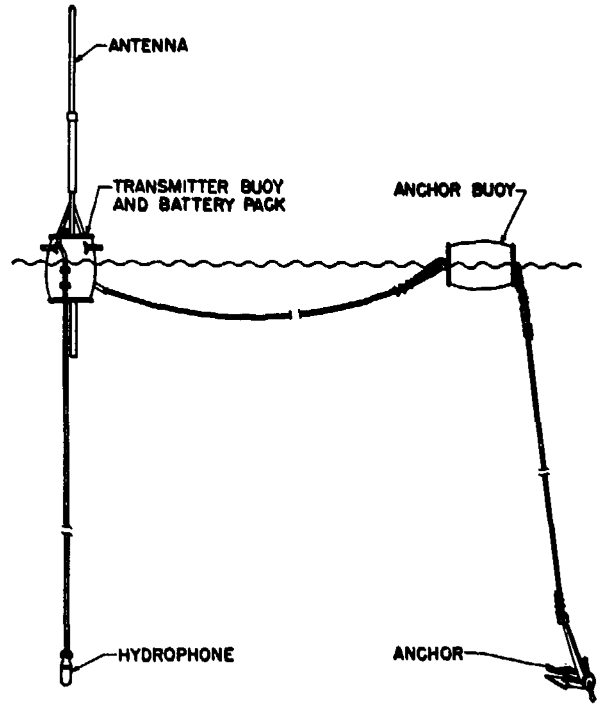


FIGURE 10. Diagram by JM buoy in the water.

EXPERIMENTAL TRANSMITTER

As a result of the experience gained with the JM buoy a new experimental transmitter was designed and constructed to fit into the JM transmitter housing.

Low microphonics, high audio gain, frequency multiplication, greater frequency deviation, and increased radio signal intensity were featured in the new transmitter. Increased audio and radio range as well as improved frequency stability were all clearly evident, but the frequent (every 3 days) servicing, necessitated by the limited battery space of the JM design, caused its abandonment.

14.7.2 The JM-1 Model

The JM-1 model incorporates a number of the features found desirable in the JM design. Among the more important design features are the heater-type tubes, high audio gain, low microphonics, and pre-emphasis of high frequencies.

Figure 9 shows how this buoy appears in the water, and Figure 11 how the components are related. Since, in this model, the battery pack is housed in the anchor buoy, a battery cable as well as a tie cable is needed between the two buoys. The added battery space affords added battery capacity and thus extends service periods to 20 days or more.

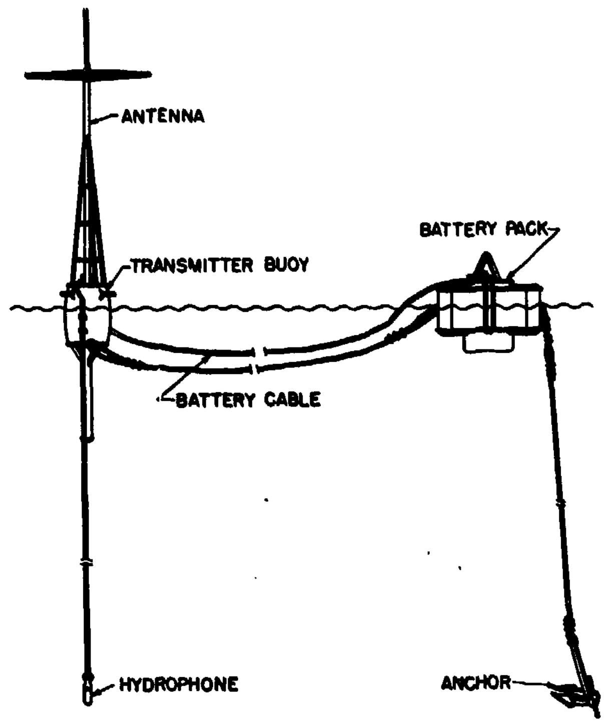


FIGURE 11. Diagram of JM-1 buoy in the water.

The use of pre-emphasis of high frequencies in the transmitter had been recommended as a result of accumulated experience in underwater listening. It was known that higher frequencies are very useful in detection and that the energy content of underwater noise decreases fairly rapidly with increase in frequency. However, self-noise in a receiver increases with frequency. Above a certain frequency, with uniform amplification in both the receiver and the transmitter, receiver noise masks the reception of the desired underwater sounds. This difficulty can be overcome by emphasis of the high frequencies in the buoy transmitter and the de-emphasis of these frequencies in the shore

receiver. This achieves a highly desirable increase in signal-to-noise ratio in the critical h-f region at the cost of a readily tolerable decrease in this ratio at lower frequencies.

After completion of laboratory tests and measurements, the JM-1 model was anchored in 185 feet of water at a distance of about 8 miles from the receiver. For several days the buoy operated satisfactorily and many ships were heard. However, during a severe storm one night the buoy disappeared and no trace of it was found.

On the basis of the laboratory and field tests completed, researchers recommended development of a new buoy with increased pre-emphasis to conform to the standard FM pre-emphasis characteristic, improved frequency stability, increased maximum deviation to 75 kc, and increased mechanical strength of the buoy.

14.7.3 The JM-1 Production Buoy

The first four of the first lot of JM-1 production buoys ordered by the Navy were subjected to extensive laboratory and field tests. At various times they were anchored within audio range of a considerable amount of ship traffic. They appeared to be quite seaworthy, at least as far as summer weather and water conditions in Long Island Sound could demonstrate. However, underwater sound pickup was not ideal. Water noise generated by the transmitter buoy and the battery float tended to mask the desired signal to a degree dependent on the strength of the water current and the state of the sea.

Mechanical problems encountered in connection with the above tests included parting of the tie cable, leaky buoys, crossing and tangling of cables, and general unwieldiness of the equipment. Parting of the tie cable, originally believed to have been caused by ships overrunning the cable, was finally attributed to intercrossing of the tie and anchor cables, with a resulting sawing action. A solution was found in the use of a chain yoke fastened to opposite sides of the battery container, with a swivel for connecting to the anchor cable. With this arrangement, any crossing was cleared by the turning action exerted as the tie cable pulled against one side of the yoke. Crossing of the hydrophone cable with the tie and battery cables was eliminated by the use of floats on the latter. In order to detect leaky buoys and battery containers before planting the buoys, air pressure of several pounds pumped into each unit was released. The rate of drop in pressure was observed on a pressure gauge.

14.7.4 Training Records

In connection with the above activities a series of phonograph records was prepared for training operators of ARSB equipment. The records provided samples of noises from two types of submarines and from a number of surface craft. The series was made complete enough so that by careful study and practice the operator might acquire the ability to recognize most of the sounds usually encountered.

14.8 SUGGESTIONS

To overcome some of the difficulties encountered in the JM-1 buoy, it has been suggested that the design be altered to utilize a simple streamline buoy having the hydrophone mounted just above the anchor. The single buoy would house both the transmitter and the battery pack and thus eliminate some of the unwieldiness of the JM-1 buoy. If streamline, it would generate less water noise and, by decreasing the relative effect of wind on its movement, reduce the possibility of cable fouling. By placing the hydrophone near the anchor the disturbing effects of surface noise would be minimized. Furthermore, a fixed position would allow the use of a directional hydrophone.

The success of the *directional radio sono buoy* [DRSB], discussed in Chapter 9, makes it appear logical to apply similar directional principles to the ARSB. In this way the maximum range of detection might be increased because of the directivity of the hydrophone. In addition the indication of the actual direction of the sound would be valuable. It would seem wise, at the possible expense of added complication, to use both directional and nondirectional listening.

Chapter 15

SUBMARINE COMMUNICATION SYSTEMS

THIS CHAPTER deals with the studies and tests of two types of systems, one for submarine internal communications and the other for communications between submerged submarines and between submarines and surface craft. Where small, closely adjoining compartments or the necessity for underwater operations must be considered, a salient problem is intelligibility.

The crowded quarters and high noise levels of submarines impose difficult requirements for intelligibility on submarine internal communications. Adaptation of the 7-MC, or talkback system, involved eliminating extraneous noise picked up by the large microphones in the conning tower, control room, and on the bridge, and overcoming feedback between the acoustically coupled compartments. The main problem connected with improving the 1-MC, or general announcing system, arose at the speakers in the engine rooms where it was difficult for the operators to hear messages over the din of the motors.

The underwater telephony system described provides communications between ships rather than within a single ship. Unlike surface craft, submarines are limited, in this problem, to underwater methods which are subject to the same oceanographic factors encountered in listening. To improve intelligibility and maximum range, several methods of modulation were investigated. It is interesting to note that the use of FM, rather than increasing, actually reduced intelligibility. A single side-band, suppressed-carrier system was found to be most satisfactory.

Submarine Internal Communications System

Submarine internal communications systems, as described here, are improvements on the 7-MC (talkback) and 1-MC (general announcing) systems adapted for submarines from similar surface ship installations. The project described was primarily a set of studies and tests aimed at overcoming some of the innate difficulties encountered in setting up a system of internal communications on a small vessel. Change from large sensitive microphones to close-talking ones in the conning tower, control room, and on the bridge answered salient noise problems of the 7-MC system. Increased speaker level with attenuation at the operator's ears remedied outstanding shortcomings of the 1-MC system. Observations and tests followed by improvements and further recommendations were carried out by the New London Laboratory. Trial installation of equipment based on the recommendations showed an improvement in intelligibility.

15.1 INTRODUCTION

The complexity of new equipment developed to aid in the operation of submarines imposed severe requirements on the performance of internal communications systems. Better intelligibility and greater coverage were held essential. In an effort to provide a solution, the 1-MC and 7-MC systems had been adapted from similar surface ship installations. However, because of the markedly different construction and the highly specialized communication requirements of submarines, serious difficulties developed in the operation of these systems. Modifications of the systems were recommended and carried out in a trial installation on a submarine. Tests made of these modifications showed that sentence intelligibility under most conditions of ship operation was increased to excellent as contrasted with the fair-to-poor intelligibility existing previously.

As furnished, the 1-MC system provides loudspeakers in each compartment and microphones in the conning tower and control room. The 7-MC system employs loudspeakers and

transducers and serves only the bridge, conning tower, control room, and the forward and after torpedo rooms, with provision for talking from any of these stations to all of the others.

18.2 EARLY TESTS

The 1-MC System

Early observations and articulation tests[1,2] indicated that the 1-MC system in its original form gave generally satisfactory performance, but fell short of requirements in the engine rooms with the diesels operating, where the ambient noise level at times approached the threshold of feeling. Three 25-watt speakers are provided in each engine room and adequate power is available in the 1-MC system to override the ambient noise sufficiently from a physical standpoint. Physiologically, however, a signal-to-noise ratio which would be adequate for intelligibility at lower levels does not give good results when the ambient noise is near the threshold of feeling. Under these conditions the ear's response is relatively insensitive to amplitude differences. To improve intelligibility, both the signal and the noise must be made less intense at the ear.

The 7-MC System

Articulation tests on several typical 7-MC system installations indicated that the sentence intelligibility over this system was no better than fair to poor for most conditions of ship operation. The 7-MC system, susceptible to noises and feedback, did not provide satisfactory communication. Major difficulties resulted from excessive wind, sea, and exhaust noise from the speaker-microphones on the bridge, noise pickup during certain conditions of ship operation, and acoustic feedback resulting from close acoustic coupling between the speakers and speaker-microphones.

Wind Noise. Laboratory tests with a bridge speaker and a fan indicated the major source of wind noise to be pulsations generated at two holes opening into the space behind the diaphragm. Since the holes are necessary to allow flooding of this space when the ship submerges, a collar was designed which prevented wind from blowing across them but at the same time allowed water to flood the unit normally. In addition, a fine mesh screen across the front face of the diaphragm reduced the wind velocity. These measures reduced the wind noise by 10 to 12 db.

Feedback. Relocation of the speakers in the conning tower and control room represented an attempt to reduce acoustic feedback. Trials indicated that it was possible to reduce the feedback appreciably by this means, but the resultant speaker locations were not generally satisfactory for adequate coverage of the compartments. No rule could be made for best speaker location even from the standpoint of feedback alone, presumably because of minor individual ship differences in the location of other pieces of interfering equipment.

Recommendations

These tests and observations led to the conclusion that problems involving feedback, location of speakers, reduction of noise pickup, and optimum adjustment of speaker levels could best be solved in the 7-MC system by divorcing the dual function of the speakers (then used as both speakers and microphones) and providing close-talking microphones in the conning tower and control room.

18.3 MICROPHONE PERFORMANCE TESTS

Close-Talking Microphones

Articulation tests were made under operating conditions to compare the performance of several close-talking microphones in the 7-MC system with the performance of the original speaker-microphone. These tests supported the conclusion that the close-talking units yielded considerably improved intelligibility. They also confirmed previous qualitative tests made in the laboratory which had indicated that a wide-range, electromagnetic headset receiver used as a microphone gave excellent speech intelligibility. The frequency-response characteristic of this unit is shown in Figure 1.

Speaker-Microphones

The 7-MC speakers operated satisfactorily as microphones only under the quieter conditions of ship operation and then only after the units in the control room and conning tower

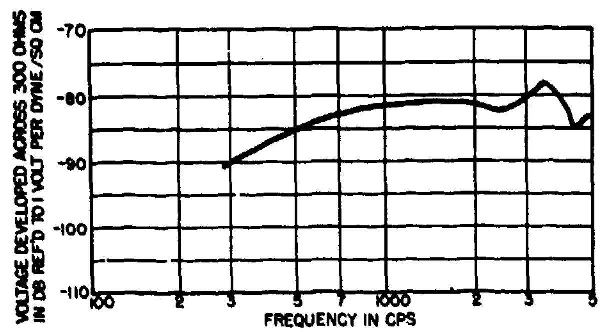


Figure 1. Frequency response characteristic of Permoflux ANB-H-1A receiver used as a microphone.

had been painstakingly placed for maximum reduction of feedback rather than in the optimum locations for coverage of the compartments.

Recommendations

At the conclusion of these tests it was suggested that an improved 1-MC system provide an automatic means of lowering the engine-room speaker levels when diesels are not running and provide ear plugs for use of the engine-room crew when diesels are running. It was also recommended that a modified 7-MC system substitute multiple close-talking microphones in the conning tower and control room for the speakers then being used as microphones. To provide for better sound distributions in the conning tower and control room, installation of two speakers each in these compartments was suggested. In compartments where the ambient levels were subject to large variations, an automatic means of boosting the level from loudspeakers was recommended. Insulation of all loudspeakers from the hull or bulkheads by means of vibration-insulating mounts could prevent feedback due to mechanical vibration. The mounts should be stiff enough for the mechanical-resonance frequency of the speakers to be low compared to the peak-response frequency of the electroacoustic system. Minor innovations would include a handset for auxiliary use on the bridge, circuits which would eliminate the necessity for using press-to-talk switching at the key station, separate circuits for each external station to reduce the possibility of flooding-out failure of communications, and bridge pickup units designed to reduce or eliminate wind noise.

Although no original work was undertaken on the determination of signal-to-noise ratios or pass-band requirements for optimum intelligibility in the presence of noise, the works of H. Fletcher and N. R. French[3,4] on those subjects were freely consulted. However, some studies were made of the characteristics of the noise in various compartments of several submarines. These studies revealed that maximum noise energy was below 1,000 c in most instances. Higher frequency components were found, however, in sounds from escaping air, certain types of low-pressure blowers, diesel engines at high speeds, etc. Thus all frequencies had to be considered in modifying the system.

15.4 THE MODIFIED SYSTEM

Modifications in accordance with the above recommendations were incorporated in a typical 7-MC installation on a new submarine. Circuit changes were confined almost wholly to changes in the ship's wiring and to the provision of new switching arrangements.[2] Five close-talking microphones were installed in the conning tower, two in the control room. The microphones were adapted from wide-range, electromagnetic headset receivers installed in 1-MC microphone cases with press-to-talk switches. The locations of these microphones in the conning tower are shown in Figure 2. Control-room microphones were located at the diving officer's station and near the radar station. Provision was made for raising and lowering the loudspeaker levels by means of a pressure-actuated switch in the low-pressure blower lines in the control room and by periscope limit-switches attached to the diesel exhaust valves in the engine rooms. Tests, observations, and discussions with Navy representatives indicated the desirability of three additional features in the modified system. Because of the high noise level in the torpedo

rooms during firing, installation of close-talking microphones there in addition to those in the conning tower and control room would simplify communications during an attack; a close-talking microphone on a short gooseneck to be plugged in on the bridge could be used in place of the handset or speaker microphone when desired; and provision for switching the forward and after torpedo-room speakers on and off from the conning tower would simplify operations and reduce noise.

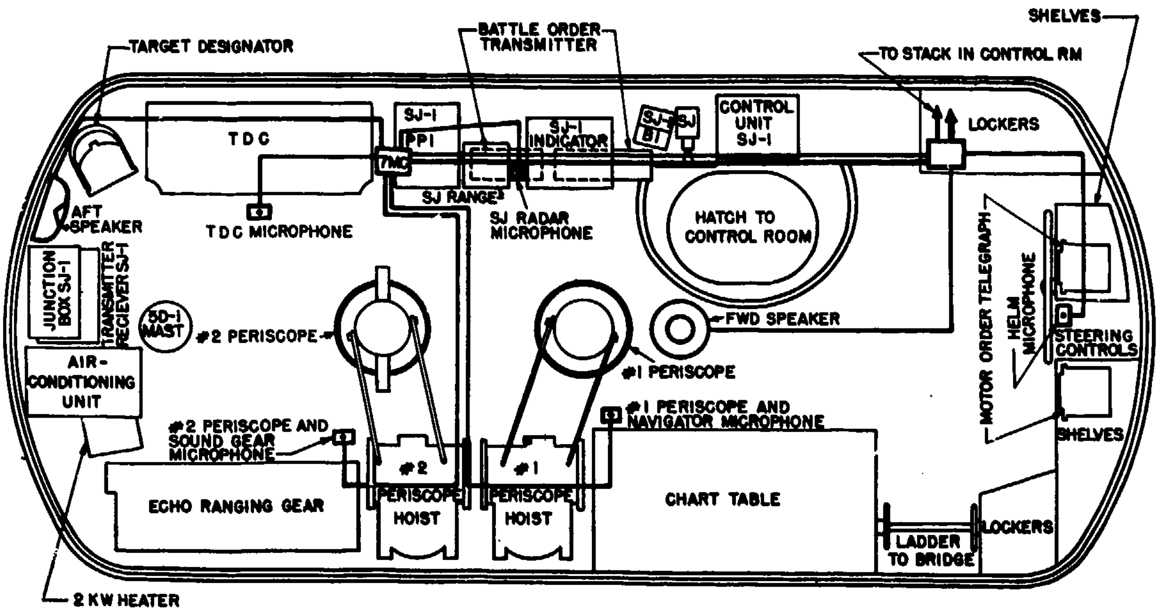


FIGURE 2. Location of 1-MC microphones and speakers in submarine conning tower USS *Becuna* (SS319).

Comparison of Articulation Percentages

A comparison of all the articulation percentages from the early tests on unmodified 7-MC systems using speaker microphones with those obtained using the wide-range, close-talking microphones is given in Table 1. These articulation tests were conducted at sea under actual operating conditions. In each case three of the submarine's officers were employed as talkers from every station under all conditions of operation. Each spoke 50 words from a standardized articulation word list. Two to four laboratory representatives at different receiving stations recorded the words heard over the system. The results were checked for the percentage of correctly heard sound—so-called letter articulation. Each figure reported in the table represents the average number of correctly heard sounds out of a total of several hundred spoken words. It is generally considered that letter articulation below 60 per cent is indicative of poor sentence intelligibility, whereas above 80 per cent gives excellent intelligibility.

TABLE 1. Comparison of letter articulation percentages obtained in tests on submarines having modified and unmodified 7-MC systems.*

Operating conditions	Unmodified 7-MC system	Unmodified 7-MC system	Modified 7-MC (close-talking microphone)	Modified 7-MC (close-talking microphone)
Day attack (submerged)	58	59	92	90
Night attack (surfaced)	47	68	94	90
Blowing up (surfaced)	26	No data	85	87

* The reader is cautioned not to place too much emphasis on the exact differences in percentage between the modified and unmodified scores in the above comparison, as unavoidable differences in the tests may be reflected in the percentages obtained. However, the broad aspect of the comparison, contrasting fair-to-poor intelligibility on the earlier boats with excellent intelligibility on the later ones having modified systems, is valid.

15.5 CONCLUSIONS

This development program was undertaken to provide modifications which could be applied to existing equipment as quickly as possible in wartime. Although the modified 1-MC and 7-MC systems yielded improved results over the first systems, they fell short of optimum performance in a number of ways.

Incorporation of a close-talking microphone permanently installed on the bridge, improved switching relays for both systems, and a conveniently controllable microphone switch for the helmsman would represent important improvements in the modified system.

A permanently installed, close-talking microphone on the bridge is necessary to insure maximum reduction of noise from wind, sea, and diesel exhausts. No unit which withstands pressure to the necessary degree and which has the required sensitivity, fidelity, and ruggedness was available.

It is important for communications systems for this type of service to be as completely reliable as possible under all conditions of ship operation; thus they should require a minimum of field servicing. The circuit switching in both the 1-MC and 7-MC systems employs a considerable number of relays which are not wholly proof against the shock, vibration, and high-humidity conditions likely to be encountered. The relays should either be eliminated or reduced in number, or a type of relay should be developed which will stand up better under adverse operating conditions.

The helmsman is required to acknowledge commands, and his means of communication with other compartments and the bridge is limited to the 7-MC system. Because of the type of operation provided by this system he must use one hand for press-to-talk switching. This is not always feasible, particularly when the ship is maneuvering in close quarters. Provision should be made, possibly by means of a foot switch, to permit the helmsman to use the 7-MC system without hand switching. It is imperative, however, if the present general type of operation is retained, that adequate protection be provided against inadvertent operation of the helmsman's switch.

FIGURE 3. Prototype model transmitting equipment for underwater telephony system.

Underwater Telephony System

This experimental underwater telephony system was designed by CUDWR-NLL to provide for voice communication between submerged submarines or between a submerged submarine and a surface ship. The system utilizes submarine supersonic equipment [WCA-2] plus voice-frequency transmitting and receiving circuits with their associated filters, a carrier wave generator, and a power amplifier capable of delivering approximately 100 watts of undistorted power to the transducers. The system proposes a single side-band suppressed-carrier type of transmission in which the signal was found to be less subject to distortion than the signal in an FM system for underwater transmission. A carrier frequency of 26 kc is used, a frequency at which the transmitting and receiving transducers are highly directional. A system operating at 8 kc was also investigated. Such a system can provide greater range but less directionality with the same transducers used in the high-frequency system. In tests of

experimental 26-kc models, consistent ranges of 10,000 yards to 15,000 yards were obtained in deep or shallow water. It was found that excessive reverberation was less troublesome with this type of communication than with echo-ranging code communications.

15.6 INTRODUCTION

Certain types of naval operations require communication between submerged submarines and other submarines or surface ships in the same vicinity. Code signaling with standard echo-ranging equipment meets this need in some measure but as this method is slow and not always reliable in areas where underwater reverberation is high, communication by means of voice-modulated supersonic waves was proposed. Experimental work was undertaken to evaluate this type of transmission and, if possible, to develop a suitable transmitting and receiving equipment.

First consideration of the factors affecting underwater sound transmission suggested that frequency modulation rather than amplitude modulation would yield the more satisfactory performance. Thorough field tests of equipment employing frequency modulation failed to show the expected results, however, and later tests of amplitude-modulated equipment indicated greatly superior performance.

This experimental work led to the development of an experimental amplitude-modulated underwater telephony system employing single side-band, suppressed-carrier features and capable of providing good speech intelligibility at maximum ranges of 10,000 to 15,000 yards. Operating on a carrier frequency of 26 kc, it utilizes existing supersonic gear, with slight modifications. Two prototype models of the equipment installed on submarines at Pearl Harbor performed satisfactorily.

15.7 PRELIMINARY SURVEY OF THE PROBLEM

As a result of previous experience it is known that any underwater communication system utilizing supersonic waves is influenced by a number of factors.

1. Transmission loss suffered by a single-frequency supersonic tone in traveling several thousand yards through the water may vary as much as 20 db in an interval of a few seconds.
2. Multiple transmission paths often cause excessive reverberation which frequently masks the intelligibility of supersonic code signals.
3. Background noise, always present in the water, and the noise produced by motion of the receiving vessel limit the range of useful transmission.

In power-line carrier-current transmission of voice-modulated signals, such factors as transmission loss variations, interfering noise, and impedance irregularities are similar to the limitations encountered in underwater sound transmission. In frequency-modulated systems with power-line carrier transmission, the limiting action of the receiver and characteristic behavior of the discriminator overcome the troublesome effects of transmission loss variations and improve the effective signal-to-noise ratio. It was expected, therefore, that similar equipment might be equally successful in the case of underwater voice communication.

15.8 INVESTIGATION OF FREQUENCY-MODULATED TRANSMISSION

Power-Line Carrier System

In assembling gear for investigating the feasibility of frequency-modulated supersonic voice communication, advantage was taken of equipment already available. The General Electric FM power-line carrier equipment, using an intermediate frequency of 175 kc which could readily be retuned to the intermediate frequency used by the echo-ranging receiver, was well adapted for use with the power amplifiers, transducer coupling circuits and transducer available in the WCA-2 echo-ranging gear already on submarines. The equipment needed for the tests, therefore, in addition to the standard echo-ranging gear, included only a special FM receiver and the low-level portion of the power-line transmitter.

A one-way transmission system utilizing

these components and capable of delivering an electric input of approximately 5 watts to the JK transducer was installed on two surface ships for sea tests.[5] In this equipment the receiver had a sensitivity of approximately 50 μv at its input terminals. Although transmission was reasonably successful with ranges up to 5,000 yards using a carrier frequency of 27 kc and up to 1,500 yards using 70 kc, reception was characterized by background noise. It was thought that this was possibly due to inadequate range in the limiter.

Improved System

Believing that reception might be improved with a more sensitive receiving circuit, new equipment was designed incorporating receivers of 1-μv sensitivity and providing for two-way transmission with a power input to the transducer of approximately 100 watts. Sea tests of this equipment failed to show the expected results. After the entire gear was checked and readjusted in the laboratory, further sea tests were made but the equipment still failed to perform satisfactorily. The overall performance of the system was characterized by excessive noise and by extremely variable signal levels.

It was noted that the noise increased whenever the signal was modulated. From this evidence the conclusion was drawn that it resulted from the distortion of the transmitted signal in the medium. For verification, a high-speed moving-film oscillograph was employed to make records of the output of the receiving transducer. Figure 4 shows typical oscillographic records, made with sinusoidal signals of constant frequency and amplitude impressed at the voice input terminal of the transmitting circuit. Although it was certain that the electric wave impressed upon the transmitting transducer contained negligible amplitude modulation, it is clear from the oscillograph traces that during transmission through the water the signal suffered a considerable amount of amplitude modulation by the time the wave reached the receiving vessel. The rate of occurrence (750 per second) of the sharp spurs defining the envelope of the amplitude modulation of the received signal corresponds with the frequency of the signal used for frequency modulation of the original carrier. The per cent of amplitude modulation was extremely variable, sometimes changing from nearly zero per cent to 50 or 60 per cent in the space of a few milliseconds.

FIGURE 4. Oscillograms of frequency-modulated supersonic waves after transmission through water. Original modulation 750 c at constant amplitude, carrier frequency 26 kc, receiver 1,050 yards from transmitter.

Reasons for Failure of FM System

Examination of the factors involved disclosed the reasons for failure of this type of signal to yield the expected results. Because of the nonexistence of ideal medium, every wave suffers some distortion during transmission. Frequency-modulated signals are no exception to this rule. Some of the characteristics of an FM wave, particularly its constant amplitude, require the preservation of certain phase relations among its several components. These phase relations are disturbed during transmission by interference between components received over multiple transmission paths. In the case of a high-frequency radio carrier modulated by an audio-frequency signal, the time intervals between arrivals over several paths are so short as to be entirely negligible compared to the phase differences in the transmitted wave. On the other hand, the much slower speed of propagation of underwater sound causes the time intervals between arrivals over multiple paths to be many times greater than those encountered in radio transmissions. In this instance, the disturbance of phase relations in the wave becomes so great that it completely destroys the essential characteristics of the signal. One consequence of this is the appearance of amplitude modulation. When impressed upon an FM receiver, these distortions produce prohibitive amounts of spurious audio-frequency components as well as variations in the level of the recovered signal.

Unsuccessful attempts to transmit television signals via FM waves confirm this deduction of the cause of the observed signal impairment. Here the intervals between arrival times over multiple paths are the same as in the case of radio-frequency transmission of audio signals. However, in the case of television, the frequencies of the components of the original signal are so high that the phase relations between them are defined by time intervals short enough to be comparable with those between arrival times.

The tests indicated that frequency-modulated supersonic transmission is not suitable for underwater voice communication. In view of the care with which the circuits were constructed and the accuracy with which their performance characteristics were known, the results of these tests were regarded as conclusive.

18.9 INVESTIGATION OF AMPLITUDE-MODULATED TRANSMISSION

In designing the circuits used for the final tests of frequency-modulated transmission, provision was made for amplitude-modulated signals to be transmitted and received. This permitted observation of the comparative performance of the two systems. First indications were that the performance with amplitude-modulated signals was greatly superior to that obtained with frequency modulation. Thus it was decided to investigate thoroughly amplitude-modulated underwater telephony.

Theoretical Considerations

In conventional amplitude-modulated systems, the transmitted signal contains a component of carrier frequency called the unmodulated carrier, together with two groups of side band components. Because, in reception, demodulation involves use of the unmodulated carrier, satisfactory performance can be obtained only so long as the carrier component is present in the received signal. In underwater sound transmission, however, a single-frequency tone suffers considerable variation in amplitude; at times the summation of components reaching the receiving point by different water paths may cause complete cancellation. Should this happen to the carrier component of a conventional amplitude-modulated signal there would be a concurrent failure to recover the original audio signal.

Consideration of these difficulties suggested employing a specialized type of amplitude-modulated system in which the carrier frequency is deliberately suppressed at the transmitter and reintroduced at constant amplitude at the receiver. Previous experience has shown that, in such a suppressed-carrier system, certain advantages are gained by the use of a single side band rather than the upper and lower side bands normally developed by the transmitting modulator. With a single side band, the total permissible power into the projector may be restricted to a narrower band

and the acceptance band of the receiver may be correspondingly narrower with resulting reduction of background noise components. In addition, the likelihood of undesirable interference between components, produced by intermodulation between the carrier and the corresponding components of the side bands, is avoided. In using a suppressed-carrier system for underwater telephony between vessels, one inherent difficulty is the relative motion which usually exists between the transmitting and receiving transducers. This makes it necessary to compensate for doppler shift by displacing the carrier impressed at the receiver to that frequency which the transmitter carrier would exhibit if it traveled through the medium.

Suppressed-Carrier System

Equipment. To test the performance of single side-band suppressed-carrier transmission, a transmitting system was designed consisting of a carrier oscillator generating a frequency of 26 kc, a speech input amplifier, a single side-band filter, and a high-quality power amplifier capable of delivering approximately 100 watts of undistorted power to the JK or QB transducer. For receiving, the WCA-2 echo-ranging amplifier[3] was used without change except for readjustment of the frequency of the beat-frequency oscillator.

Tests. Tests of this system on moving vessels were uniformly satisfactory. Ranges of 10,000 yards or more were consistently obtained in Long Island Sound. At ranges of more than 12,000 yards, the background noise tended to become excessive, but contact was generally not lost completely until a range of about 15,000 yards was attained. In deep-water tests, communication was possible at ranges of 6,000 and 8,000 yards in the presence of thermal gradients for which the limiting ray diagrams showed ranges to the shadow zone of only 1,000 and 1,500 yards respectively.[6]

The signal levels were invariably observed to be stable to a greater degree than could be accounted for alone by the use of a locally generated carrier, and it was found possible to attain entirely satisfactory voice communication in areas where the high reverberation level prohibited code transmission at ranges of even 1,000 or 1,500 yards. It is believed that these observations can be explained only in terms of the averaging effect attending the use of a signal having a large number of individual components. At any instant one or more of these components may be completely obliterated due to interference, but it appears that there always remain a sufficient number at normal level so that on the average the audio signal level shows little variation.

Later tests, utilizing the low-level portions of the transmitting circuits working into the QB driver indicated results which were in all respects equal to those obtained with the specially designed power amplifier originally used. These tests demonstrated that acceptable performance can be obtained by using the standard echo-ranging driver amplifier with no more modification than a careful alignment to insure that reasonable operating limits are not exceeded.

Investigation of AM 8-kc Carrier Transmission

In order to investigate the potential advantages of lower-frequency operation, a single side-band suppressed-carrier system was constructed to operate at a carrier frequency of 8 kc.[7] For transmitting, this system makes use of a 3½-inch diameter tubular magnetostriction transducer 30 inches long and a power amplifier capable of delivering 400 watts. The amplifier into which the microphone works contains a limiting circuit to provide for clipping the energy of vowel sounds with respect to that of the consonants thus permitting a greater effective power output.[8]

Standard JT sonar equipment with supersonic converter, as discussed in Chapter 10, serves as receiver. The transmitting transducer, suspended in the water with its axis vertical, is nondirectional in the horizontal plane, but the 5-foot long JT receiving hydrophone is mounted horizontally and thus is highly directive in the horizontal plane.

Brief tests of this equipment demonstrated ranges of about 13,000 yards, approximately equal to those obtained with the 26-kc system. It is believed that longer ranges were not obtained because the advantages gained in re-

duced transmission loss and speech clipping were offset by the nondirectional distribution of the available power.

The comparative merits of operation at 8 kc and at 26 kc can be completely assessed only when the conditions of use are fully specified. Greater ranges are possible at 8 kc provided the transducers are equally efficient and directive, but any transducer having directivity at 8 kc equal to that of the QB projector at 26 kc would be of greatly increased, if not prohibitive, size. The nondirective characteristic is of advantage in establishing initial contact with other vessels. Consequently, this type of transmission pattern is well suited for one-way communication from a controlling vessel to several others disposed over a wide arc.

15.10 DIRECTIONALITY OF PROJECTORS

In both the frequency-modulated and the amplitude-modulated systems using components of the WCA-2 echo-ranging equipment, the transmitting and receiving transducers are highly directional at the 26-kc carrier frequency used. Such directional beams have decided signal-strength advantages. During transmission, the intensity on the axis exceeds the intensity on any bearing from a nondirective transducer of equal acoustic output by more than 20 db, and in reception the signal-to-noise ratio is similarly improved by about 20 db. A disadvantage of using directional beams lies in the possible difficulty of establishing contact between vessels which do not accurately know their positions with respect to each other. During the tests the relative position of the two vessels was generally known with considerable accuracy, consequently no difficulty was experienced from this cause.

15.11 PROTOTYPE EQUIPMENT

In the construction of prototype equipment to be installed on submarines for field operation, the design of the 26-kc system first tested extensively on surface ships was closely followed. A schematic diagram of the transmitting circuits used is shown in Figure 5. The circuit, including V-101, constitutes a fixed-frequency oscillator for generating the carrier wave[a] which is impressed through a buffer stage on the modulator. In the balanced-ring modulator circuit utilizing varistor CR-101, potentiometer R-148 is employed to make possible the necessary balance upon which adequate suppression of the carrier and the audio frequencies depend.

Speech signal from the microphone, after amplification by a two-stage, resistance-coupled, audio amplifier, is impressed upon the varistor modulator through transformer T-107. The signal from the modulator is matched in impedance to the input of a band-pass filter Z-101, whose circuit is shown in detail in Figure 6. This filter passes the upper side-band frequencies, but strongly attenuates the carrier, the lower side band, and all other frequencies. The remainder of the circuit provides amplification of the frequency band passed by the filter. Tube V-103 acts as an inverter for driving the final stage which consists of beam power tubes in parallel push-pull. The amplifier is capable of delivering approximately 100 watts of undistorted power to the QB transducer. Figure 3 is a photograph of the prototype model of the transmitting equipment.

The audio signal used to modulate the carrier covers the 300- to 3,000-c band for the upper side band selected for transmission. Therefore, it occupies the region between 26.3 and 29 kc. At the receiving end this band is delivered to the input of the WCA-2 echo-ranging receiver[7] where, after passing through the r-f tuned circuits and r-f amplification stage, it is combined in the first modulator with a heterodyne carrier of 87.6 kc. The difference frequencies thus produced lie between 58.6 and

[a] Because of the likelihood of encountering doppler shifts, the method of generating the transmitter carrier employed by the WCA-2 equipment cannot be used for voice-modulated underwater telephony. In WCA-2 the carrier is obtained by intermodulation between the output of a fixed-frequency oscillator and a tone from the first heterodyne oscillator of the echo-ranging receiver, thus permitting the operating frequency of the system to be changed over a considerable range by adjustment of the receiver oscillator. If this means of generating the carrier were used for underwater telephony between moving vessels, it is evident that any adjustment giving satisfactory transmission in one direction would be incorrect for transmission in the other. It is necessary, therefore, to generate a transmitting carrier which is independent of the receiver oscillator.

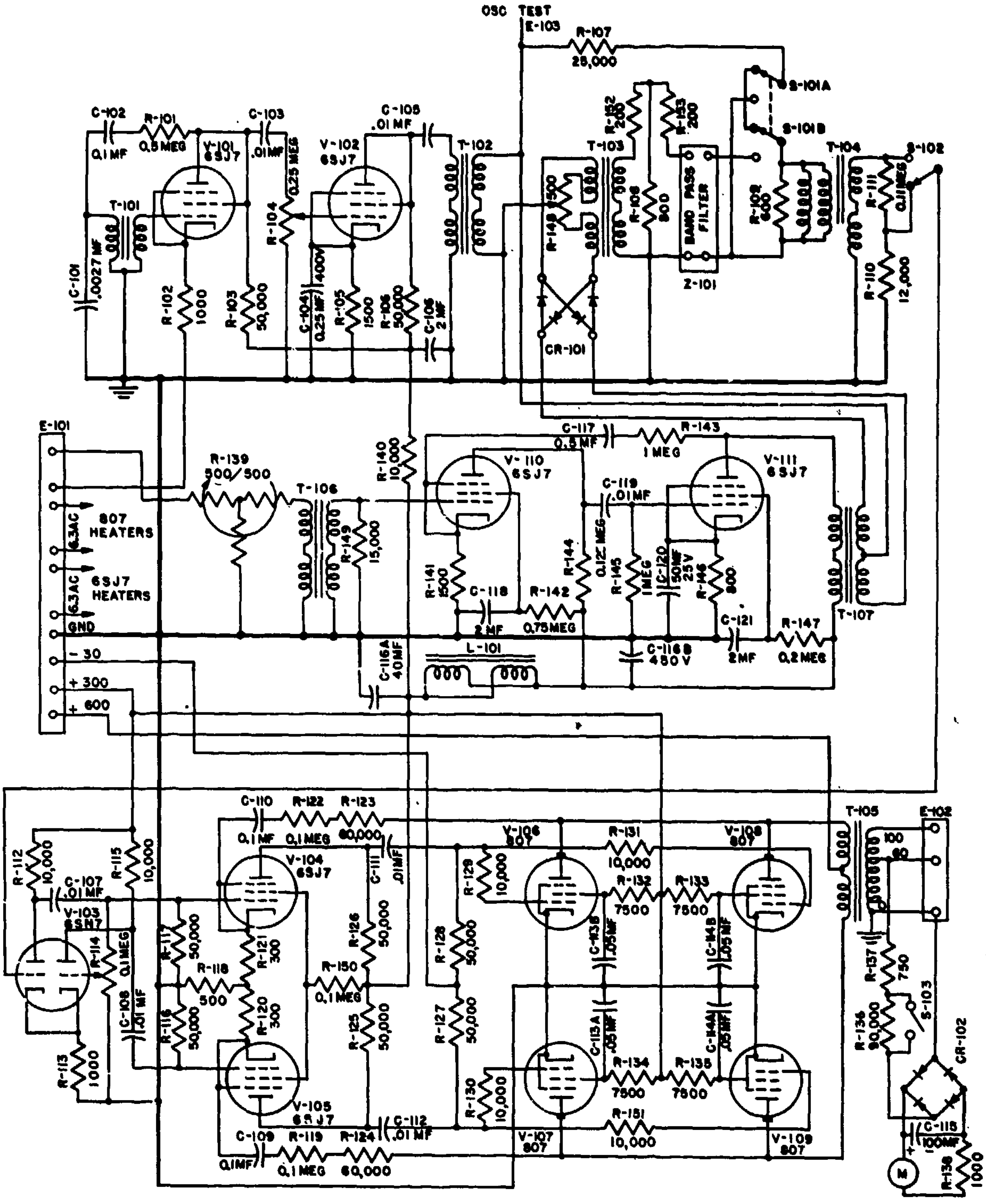


FIGURE 5. Schematic of transmitting circuits used in prototype equipment for underwater telephony.

61.3 kc, a band within the limits of the pass band of the i-f stages of the amplifier. After passing through the i-f amplifier, the 58.6- to 61.3-kc band is impressed upon the second modulator whose oscillator frequency is adjusted to 61.6 kc. The difference frequencies produced in this case cover the range 300 to 3,000 c and the original audio signal is thus

recovered without the use in the receiver of a carrier identical to that at the transmitter. Effectively, however, this 26-kc carrier frequency appears as the difference between the 87.6- and 61.6-kc frequencies of the oscillators in the receiving amplifier modulators.

In operation, if the second receiving amplifier oscillator is set accurately at 61.6 kc, the proper relation between the frequency of this carrier and the pass band of the i-f stages is insured. Thus, the frequency of the first oscillator may be adjusted to compensate for any effective doppler shift, giving distortionless recovery of the audio signal. With the first oscillator set to give a difference of 26 kc between its frequency and that of the second oscillator, it is found that incoming signals are always intelligible. The quality of the recovered speech signal then indicates the necessity for any final adjustment of the first oscillator.

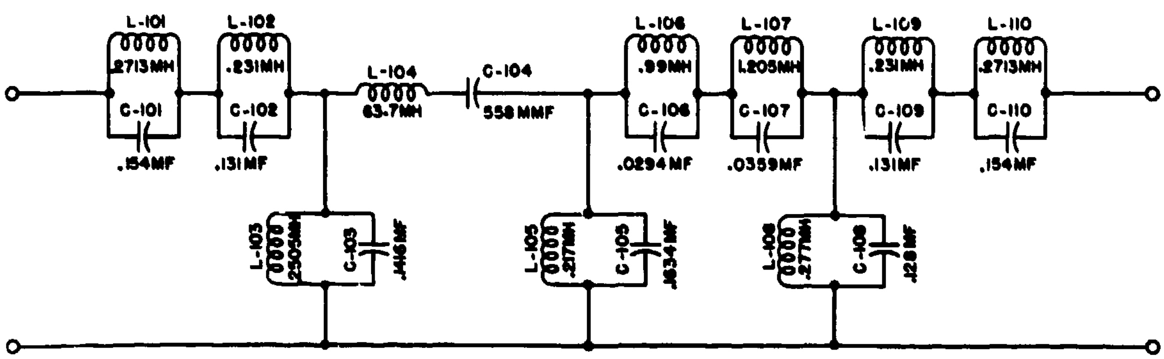


FIGURE 6. Schematic diagram of filter for selecting side band.

Sea trials of two units of this equipment, installed on submarines at Pearl Harbor,[9] resulted in consistent ranges up to 14,000 yards, with performance generally superior to that obtained in earlier tests in Long Island Sound. On one occasion, with exceptional thermal gradient conditions, satisfactory communication was possible at a range of 17,000 yards.

15.12 CONCLUSIONS

As a result of experience gained with both the frequency-modulated and amplitude-modulated systems, a number of conclusions may be drawn with reasonable assurance.

1. Any equipment designed for the purpose of providing underwater communication by voice modulation of a supersonic wave should employ the single side-band suppressed-carrier method of transmission.

2. Because attenuation of sound in the water is unlikely to average less than about 5 db per thousand yards at standard echo-ranging frequencies of 26 to 30 kc, increasing the power to the projector can in itself effect only slight extensions of the 10,000- to 15,000-yard ranges obtainable with the single side-band suppressed-carrier equipment tested.

3. If ranges greater than those obtainable with the present gear are to be sought, the most promising approach appears to be through a reduction in carrier frequency.

4. In regions where underwater reverberation prevents intelligible c-w contact with standard echo-ranging equipment, supersonic carrier telephony may provide a satisfactory means of communication.

5. The maximum range of code signaling under good conditions is generally no greater than that at which satisfactory underwater carrier telephony can be maintained.

6. In order to provide suitable underwater telephony equipment for use by submarines equipped with standard WCA echo-ranging gear, only the equipment necessary for delivering low-level signals to the input of the driver need be provided.

GLOSSARY

AFC. Automatic frequency control.

ARSB. Anchored radio sono buoy.

ASW. Antisubmarine warfare.

ATF. Automatic target follower.

BAFFLE. A shield used to modify an acoustic path.

BDI. Bearing deviation indicator.

BINAURAL LISTENING. A method of finding relative bearing between own ship and target by comparing, for different orientation of the hydrophone axis, differences in phase and arrival time of energy received at two separate channels from a single source.

CAVITATION. The formation of vapor or gas cavities in water caused by sharp reductions in local pressure.

CRYSTAL TRANDUCER. A transducer which utilizes piezoelectric crystals, usually Rochelle salt, ADP, quartz, or tourmaline.

CUDWR. Columbia University, Division of War Research.

CW. Continuous wave.

DDI. In this volume, direct deviation indicator.

DOME. A transducer enclosure, usually streamlined, used with echo-ranging or listening devices to minimize turbulence and cavitation noises arising from the transducer's passage through the water.

DRSB. Directional radio sono buoy.

ERSB. Expendable radio sono buoy.

HUSL. Harvard Underwater Sound Laboratory.

HYDROPHONE. An underwater microphone.

JK. Navy designation for a listening system using a large crystal hydrophone.

LETTER ARTICULATION. A measure of the efficacy of a communications system, expressed as the percentage of correctly-heard sounds.

LISTENING DIFFERENTIAL. Ratio of the just-perceptible change in level to the initial signal level.

MAGNETOSTRICTION EFFECT. Phenomenon exhibited by certain metals, particularly nickel and its alloys, which change in length when magnetized, or (Villari effect) when magnetized and then mechanically distorted, undergo a corresponding change in magnetization.

MG. Motor-generator.

MIT-USL. Massachusetts Institute of Technology, Underwater Sound Laboratory.

MVP. Merchant vessel protection.

NLL. New London Laboratory.

NLM. Noise level monitor.

PROJECTOR. An underwater acoustic transmitter.

QB. Standard Navy searchlight-type echo-ranging equipment using Rochelle salt transducers.

QC. Navy designation for standard echo-ranging gear using a magnetostriction projector.

RADAR. Generic term applied to methods and apparatus that use RAdio for Detection And Ranging.

RANGE RATE. Rate of change of range between own ship and target.

RECOGNITION DIFFERENTIAL. The number of db by which a signal must exceed the background in order to be recognized 50 per cent of the time.

REVERBERATION. Sound scattered diffusely back towards the source, principally from the surface or bottom and from small scattering sources in the medium such as bubbles of air and suspended solid matter.

REYNOLDS NUMBER. A nondimensional ratio used for comparing the conditions for similar motions in fluids. The ratio of any typical length of a body times its velocity, to the kinematic coefficient of viscosity of the fluid.

ρc-RUBBER. A rubber compound with the same ρc (density $\times$ velocity of sound) product as water.

RLI. Right-left indicator.

ROCHELLE SALT ($KNaC_4H_4O_6 \cdot 4H_2O$). Potassium sodium tartrate, a piezoelectric crystal used in sonar transducers.

SHADOW ZONE. Region in which refraction effects cause exclusion of echo-ranging signals.

SLICKS. Oils, dyes, metal powders, etc., used to mark an area on the water surface.

SONAR. Generic term applied to methods or apparatus that use SOund for NAvigation and Ranging.

SONIC FREQUENCIES. Range of audible frequencies, sometimes taken as from 0.02 to 15 kc.

SUPERSONIC FREQUENCIES. Range of frequencies higher than sonic. Sometimes referred to as ultrasonic to avoid confusion with growing use of the term supersonic to denote higher-than-sound velocities.

TARGET ASPECT. Orientation of the target as seen from own ship.

TDC. Torpedo data computer.

TDM. Torpedo detection modification.

TDS. Target designation system.

THRESHOLD OF FEELING. Level at which increasing sound intensity becomes painful to the listener.

TLR. Triangulation listening ranging.

TOWING ANGLE. Angle between the towing cable and the normal to the water's surface.

TRANSDUCER. Any device for converting energy from one form to another (electrical, mechanical, or acoustic). In sonar, usually combines the functions of a hydrophone and a projector.

UCDWR. University of California, Division of War Research.

X-CUT. A cut in which the electrode faces of a piezoelectric crystal are perpendicular to an X-, or electrical, axis.

YAW. Angular deviation from line of course taken in a horizontal plane about the vertical axis of the hydrophone housing.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-20	The Trustees of Columbia University in the City of New York New York, New York	Studies and experimental investigations in connection with the development of listening and detecting systems suitable for surface craft and for submarines.
OEMsr-1128	The Trustees of Columbia University in the City of New York New York, New York	Studies and experimental investigations in connection with methods of furnishing harbor protection by means of cables and associated equipment.
OEMsr-33	RCA Manufacturing Company, Inc., Camden, New Jersey	Studies and experimental investigations in connection with submarine and subsurface warfare.
OEMsr-692	Western Electric Company, Inc., New York, New York	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-695	Western Electric Company, Inc., New York, New York	Conduct studies and experimental investigations in connection with and for the development of equipment and methods involved in submarine and subsurface warfare.
OEMsr-346	Western Electric Company, Inc., New York, New York	Studies and experimental investigations in connection with the design and development of radio sonic buoys (capable of being dropped overboard from a ship).

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
AC-55	Development of a directional radio-sonic buoy.
NA-107	Towed submarine listening gear for use with lighter-than-air craft.
NO-163	Cooperation with the Navy in harbor surveys and surveys of ambient underwater noise conditions in various areas.
NS-102	Development of subaqueous microphones for sono-radio buoys and cable connected hydrophones.
NS-106	Expendable sono-radio buoy.
NS-113	Listening apparatus for small patrol craft and submarines toroidal magnetostriction hydrophone.
NS-198	Consultant on contracts with Emerson Radio Phonograph Corporation and Freed Corporation for manufacture of expendable sono-radio buoys.
NS-247	Triangular ranging.
NS-248	Underwater voice communication system.
NS-330	Consulting services on production of radio transmitting equipments AN/CRT-4.
NS-337	WCA conversion equipments, consulting services on by Columbia University Division of War Research to BuShips (940) on its contracts NXsr-42164 (Task 9) and NXsr-65323 with RCA.

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ABSTRACT:

This report is intended to summarize the work of the laboratories of N.D.R.C. on underwater listening devices and techniques applicable to the detection, navigation, and operation of submarine craft. The volume is not intended to serve in any sense as a textbook but as reference useful to newcomers to this specialized art as well as to those who may be interested in particular details and the reasoning behind the electronic techniques and circuitry employed. Some of the items covered in the breakdown of the subject include: PhysicalFactors Affecting the Target Signal, Bearing Indicator Systems, Submarine Triangulation-Listening-Ranging System, Torpedo Detection Studies and Systems, Harbor Protection Systems and Submarine Communication Systems.

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